Sonder les milieux opaques avec de la lumière:
De l'imagerie aux études fondamentales

Sylvain Gigan

Séminaire Collège de France

Chaire « atome et rayonnement »

06 Juin 2018

Laboratoire Kastler Brossel
Physique quantique et applications

ENS
SORBONNE UNIVERSITÉ
COLLÈGE DE FRANCE
cnrs

Team / Collaborations / Funding

The Team

Post-docs

PhD students

Claudio MORETTI

Hugo DEFIENNE

Awoke NEGASH

Saroch LEEDUMRONG WATTHANAKUN

Tom SPERBER (codir: P. Sebbah)

Baptiste BLOCHET (codir: L. Bourdieu)

Antoine BONIFACE

Jonathan DONG (codir: F. Krzakala)

Interns: L. DEVAUD, R. BASALGETE, L. BLUM MOYSE

Former PhDs: S.Popoff (CNRS), D.Andreoli, P.Bondareff, T.Chaigne, H.Defienne, M. Mounaix
Former postdocs: D.Martina, G. Volpe (UCL), J.Bertolotti (U.Exeter), O.Katz (H. U. Jerusalem), R. Savo (ETH), T. Juffmann (U. Wien) J. Gateau (CNRS)

Collaboration @ ESPCI
M. Fink
C. Boccara
P. Sebbah
S. Bidault
S. Grésillon
R. Carminati
R. Pierrat
G. Lerosey

Collaboration @ ENS
L. Bourdieu (IBENS)
F..Krzakala (LPS)
F. Pincet (LPS)
R.Thiam (LPS)
H. Barbosa de Aguiar (ENS)
N. Treps (LKB)

Collaborations: National and International
S. Rotter (TU Wien)
S.Brasselet (Institut Fresnel)
I.Walmsley, B. Smith (U. Oxford)
R. Sapienza (King's College)
G. Volpe (UCL London)
O. Katz (U. Jerusalem)
E. Bossy (UJF Grenoble)
M. Paternostro (U. Belfast)
R. Di Leonardo, M. Barbieri (U. Roma)
R.Piestun (U. Colorado, Boulder)
O. Muskens, R. French (U. Southampton)
F. Soldevila, E. Tajahuerce, J. Lancis (Castellon)

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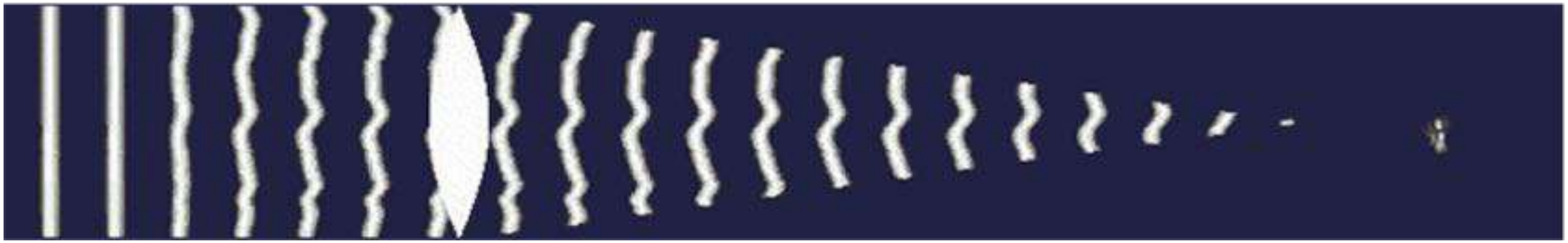
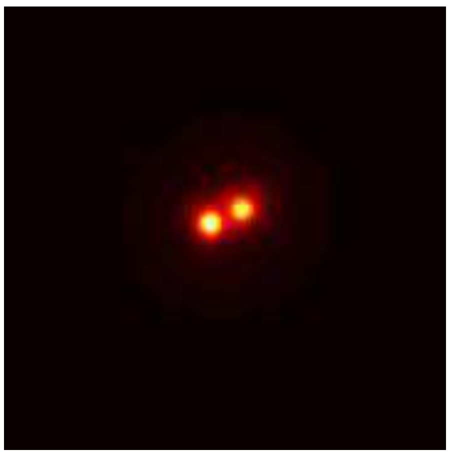
Wavefront perturbation



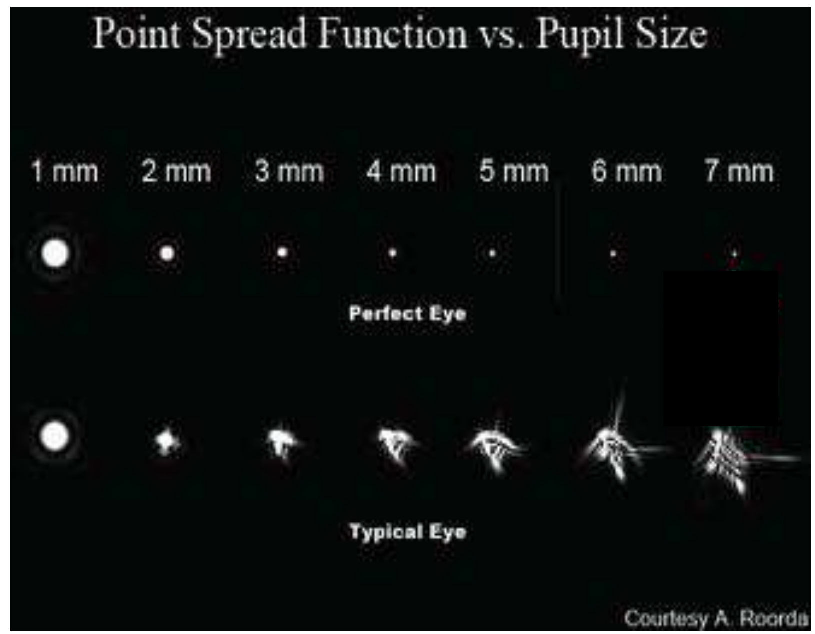
Astronomy : twin star



Diffraction limited

With atmospheric aberrations

In biology : eye aberrations



SOLUTION : MEASURE and CORRECT the wavefront

Conventional adaptive optics

Courtesy: F. Lacombe/observatoire de Paris

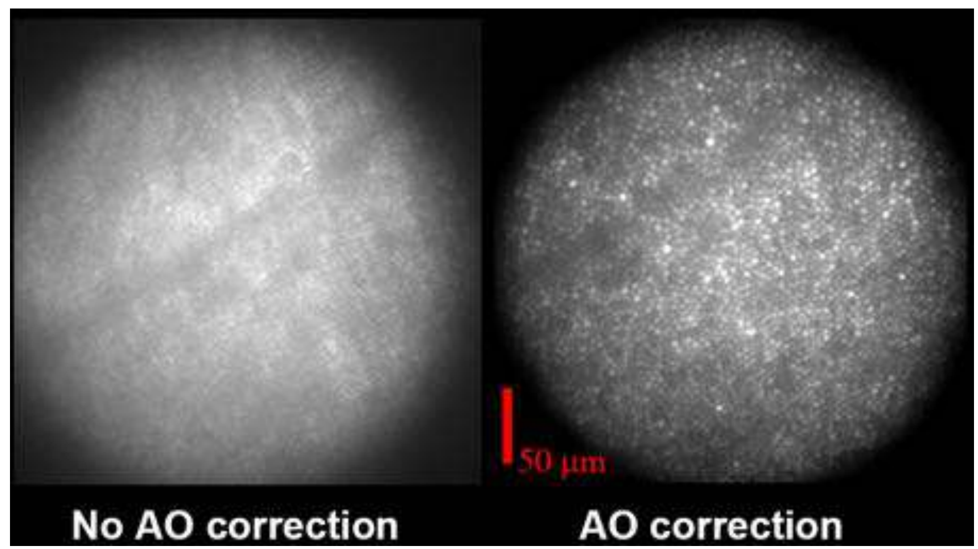
Correction device (déformable mirror)

Imaging (CCD)

Wavefront measurement (shack Hartmann)

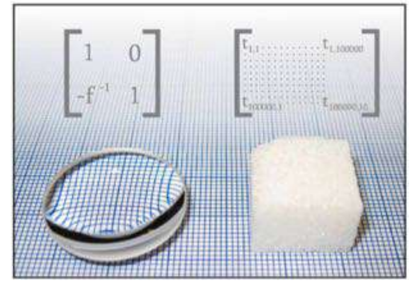
Real-time control

Retinal Imaging



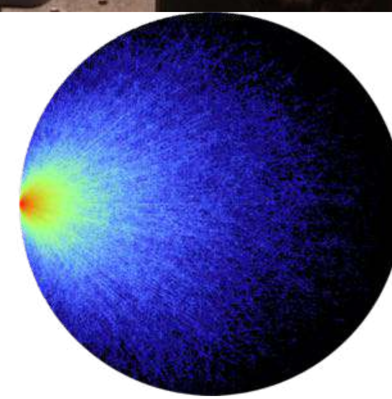
Outline

1- Wavefront Control in complex media



2- non-invasive imaging through
a thin scatterer

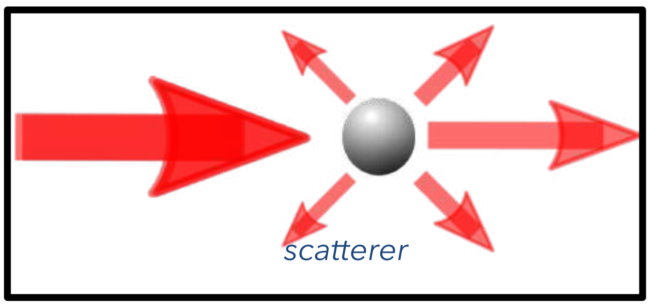
3- A fundamental invariance property of light



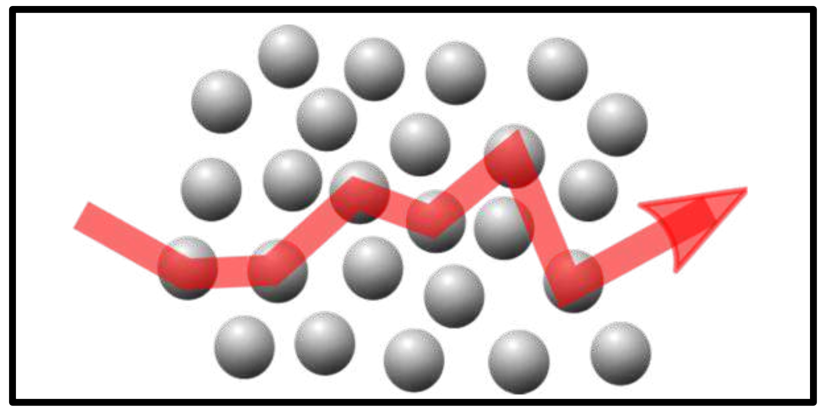
Scattering “Opaque” media

- In strong heterogeneous media, transport of light is affected by <u>**scattering**</u> effects

With a single scatterer: microscopic scale



With multiple scatterers: mesoscopic scale



- Important mesoscopic quantities:
  - ➢ l_s scattering mean free path: mean distance between scattering events
  - ➢ $l^\star$ **transport mean free path:** distance of propagation over which light loses its initial direction


Direct light
Single scattering (Rayleigh)
Multiple scattering (Mie)
Deep multiple scattering

The grand challenge in deep optical imaging

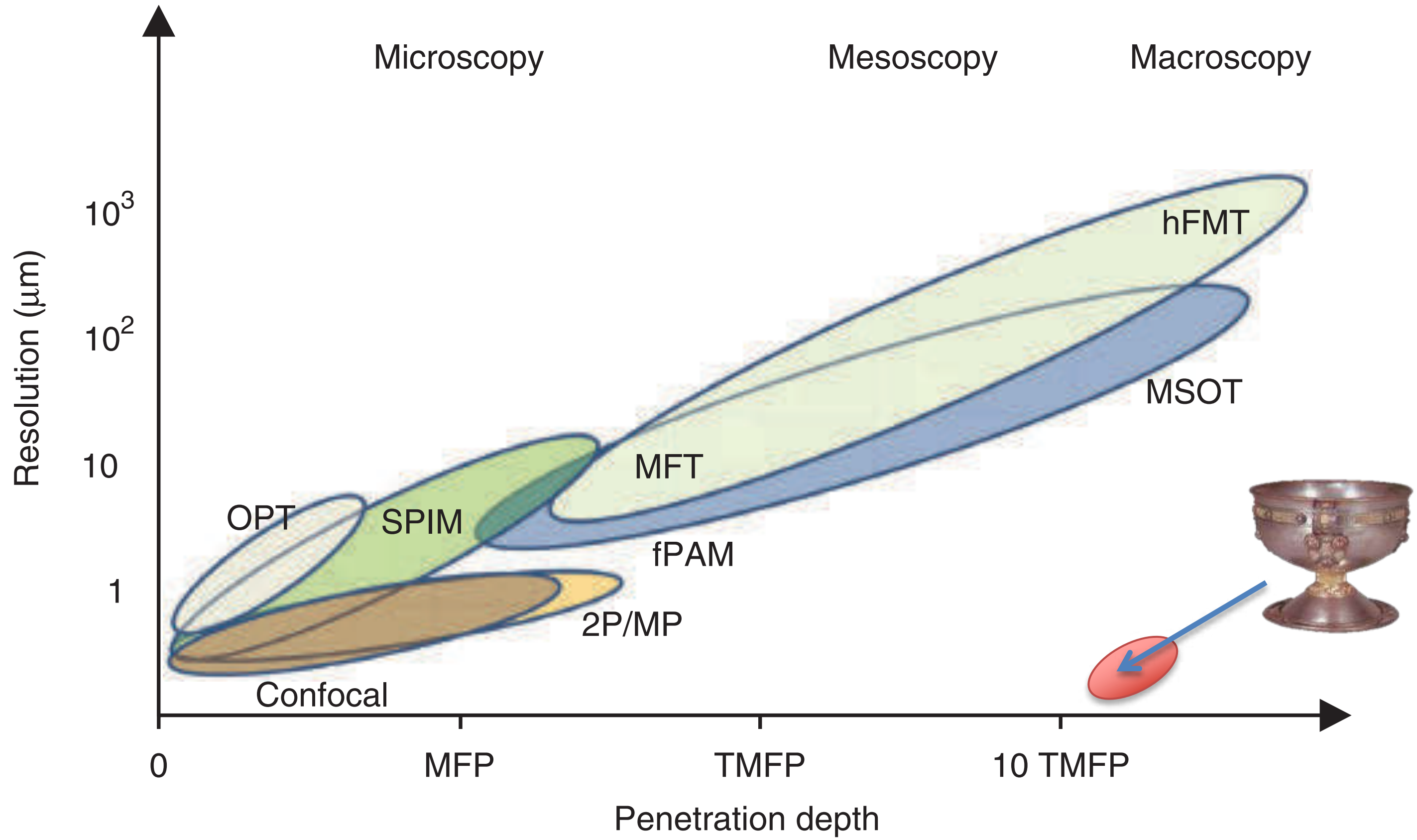
LKB

Ballistic light is <u>exponentially</u> attenuated with the scattering mean-free-path (MFP)

TWO ISSUES :

✗ « Ballistic » microscopy fails when going deep in a scattering medium

✗ « Diffuse » imaging in depth has a very low resolution (mm-cm)

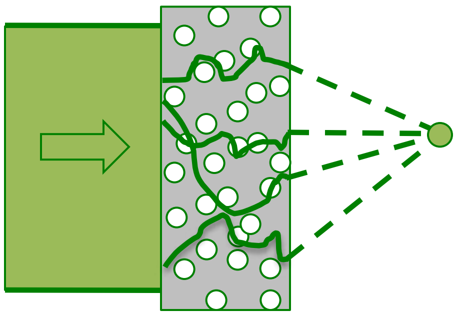


V Ntziachristos, **Going deeper than microscopy: the optical imaging frontier in biology**, Nature Methods (2010)

S. Gigan, « Feature » **Optical microscopy aims deep**, Nature Photonics 11, 14–16 (2017)

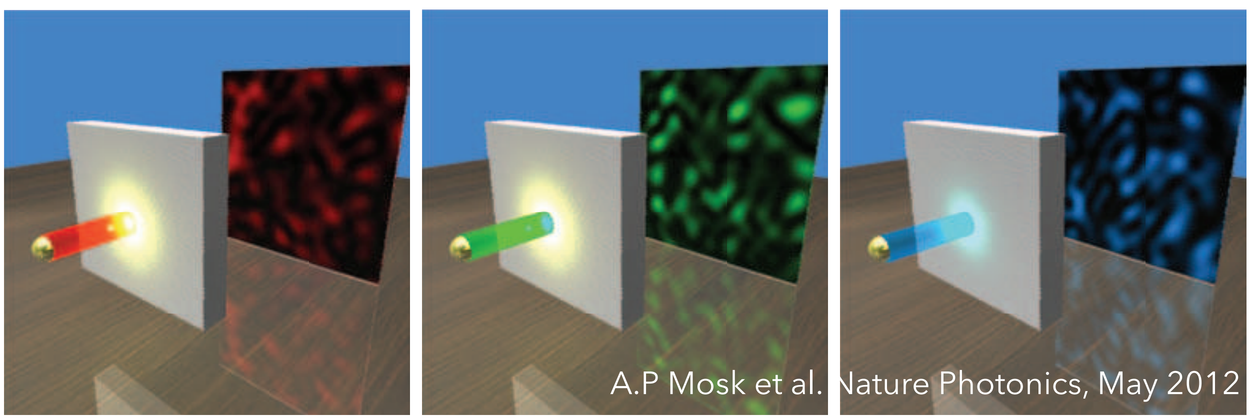
The speckle figure

Monochromatic regime



A speckle grain =
- Sum of different paths with random phases
  = *random walk in the complex plane*
- Size limited by diffraction
- unpolarized speckle = 2 independent speckles

Polychromatic (i.e. temporal)

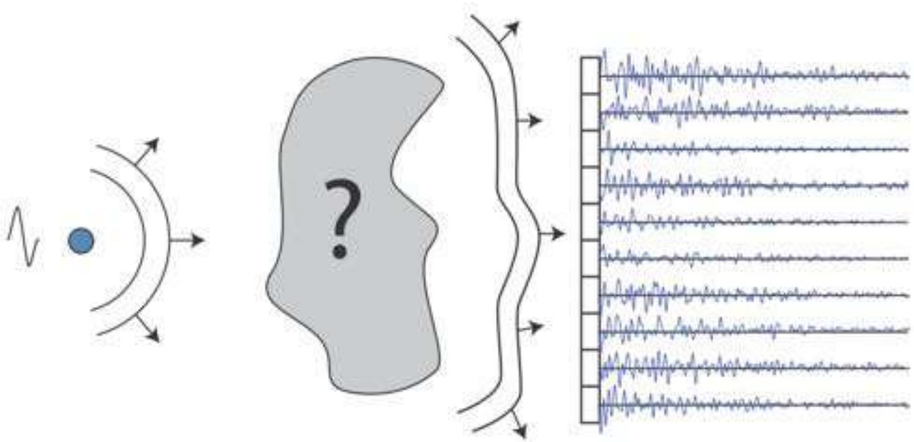


Spectral dependence
=
confinement time of light in the medium

Speckle figure : complex distribution … but **coherent** therefore **controlable**!

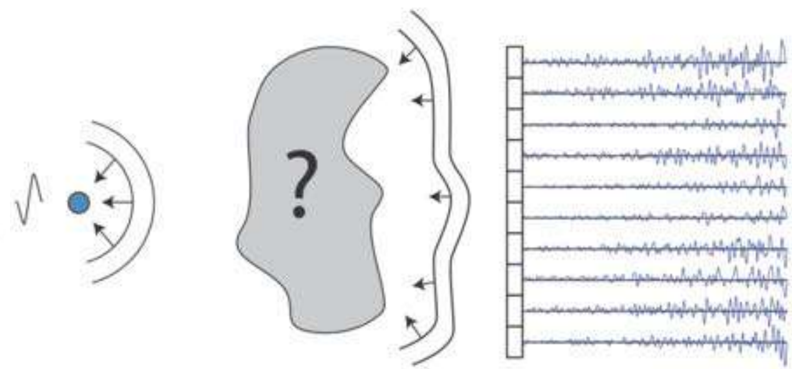
A little help from acoustics : Time-reversal techniques

Hypothesis : linearity, reversibility of wave equation



Step 1: record

Step 2: playback



Spatial and temporal focusing

A. Derode, P. Roux et M. Fink, *Phys. Rev. Lett.*, 75, 4206 (1995)

Spatial shaping tools in Optics

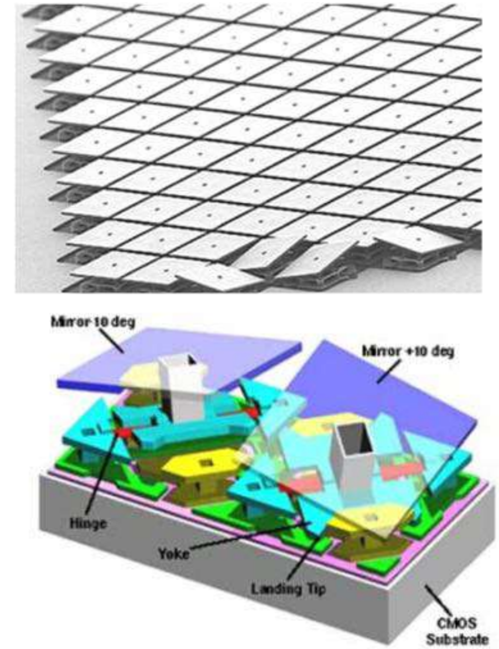
Deformable Mirrors :

10-100 actuators typical
course : 10-20 microns
Speed > kHz

Not good !

Liquid crystals
Spatial Light Modulators :
>1 million pixel
Phase modulation
course : 1 microns
limited speed : 50Hz

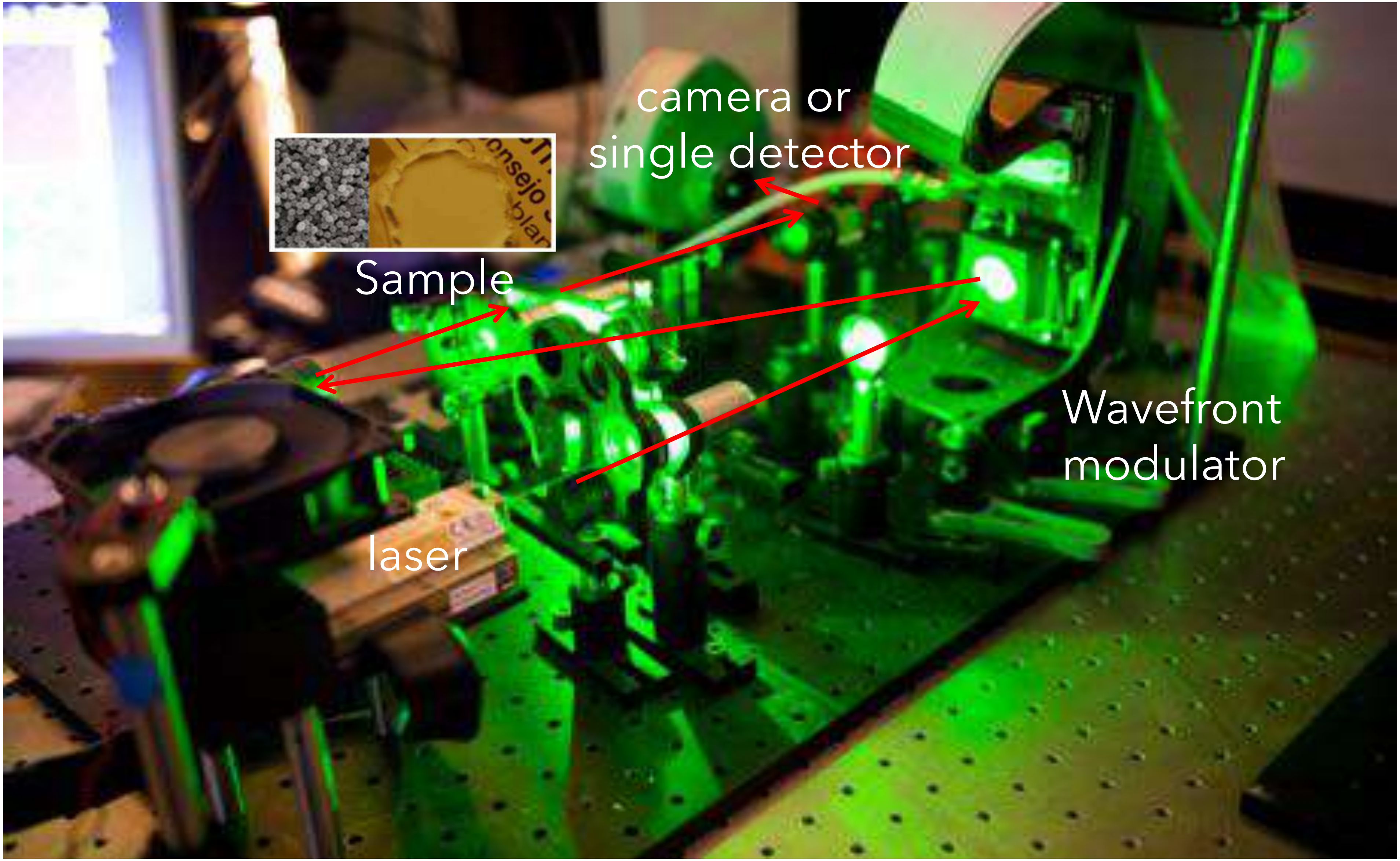
Tool of choice
…until now!



MEMS
Spatial Light Modulators :
Texas DLP/DMD
>8 million pixel
binary ON/OFF
very fast speed : 24kHz

Very promising…
…but need tweeking

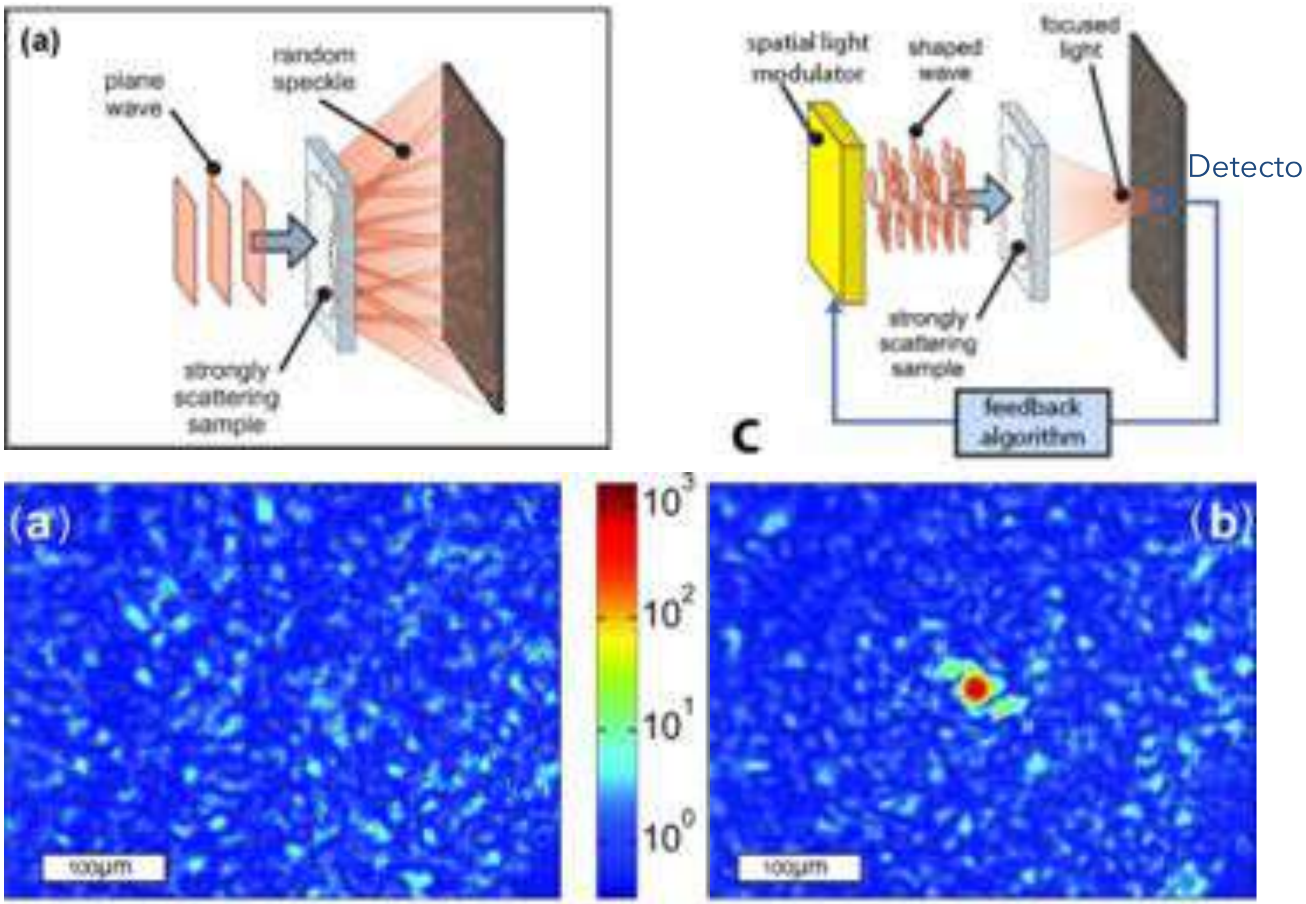
How does the experiment look like?



Wavefront shaping with CW light

Iterative optimization algorithm

No shaping | Wavefront shaping

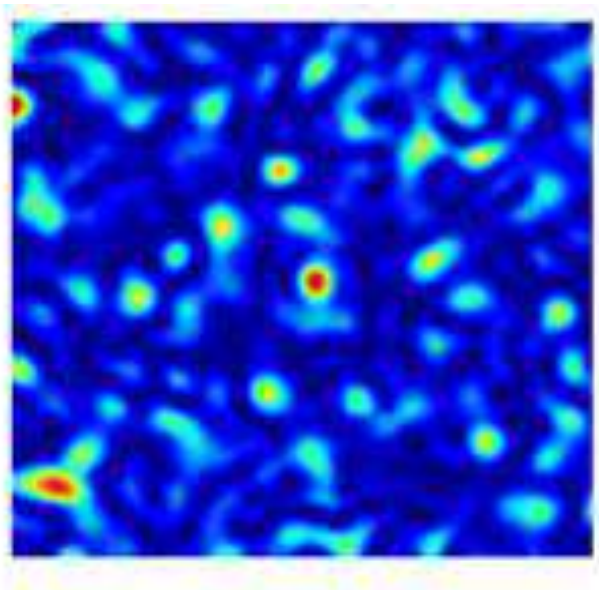


Vellekoop and Mosk, *Optics Letter, 2007*

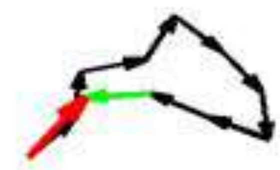
Iterative approach:
→ Optical feedback optimization

Spatial Light Modulator

Output speckle



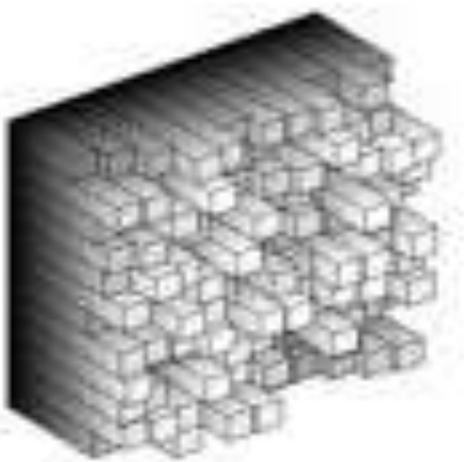
Optimization of optical intensity



(Simulations)

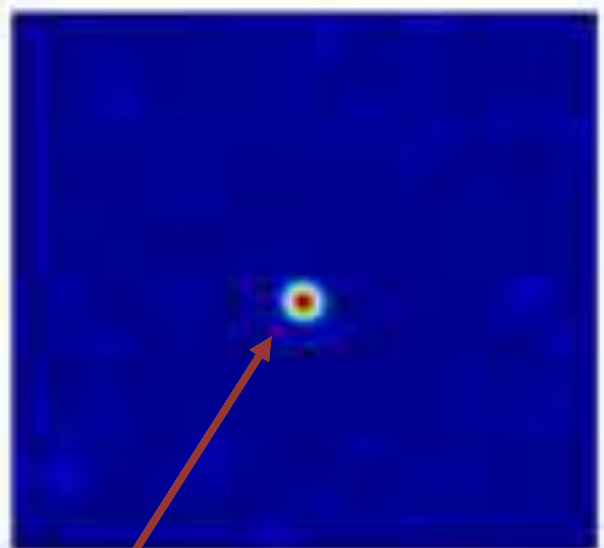
Iterative approach:
→ Optical feedback optimization

Spatial Light Modulator

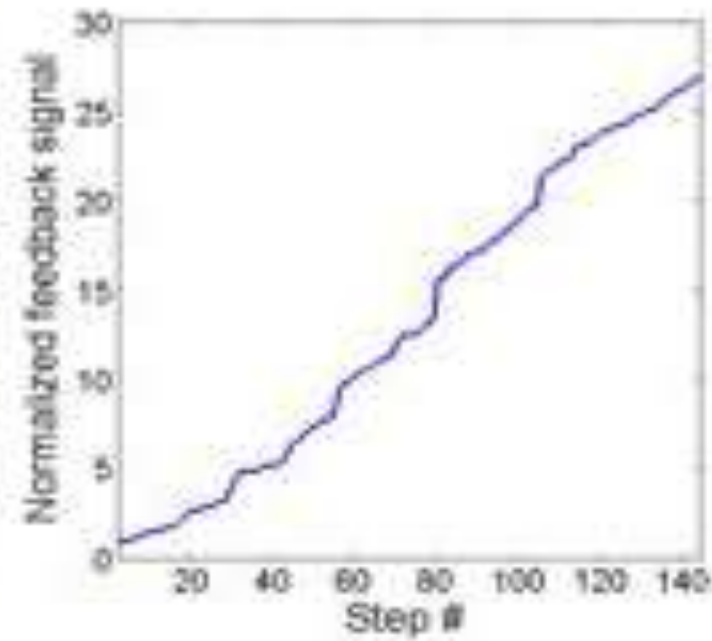


(Simulations)

Output speckle



Optimization of optical intensity



« Perfect » Point spread function Vellekoop Nat. Photonics (2010)

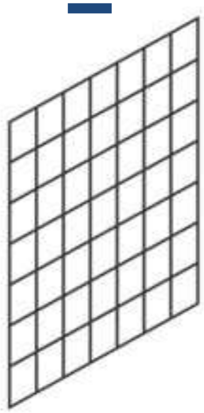
A more general approach : the transmission matrix

SLM : array of pixels

Linear system

CCD camera : array of pixels

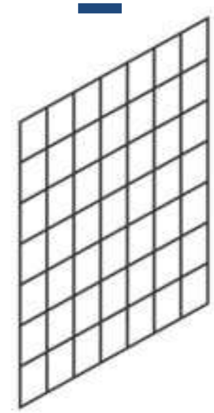
=



=

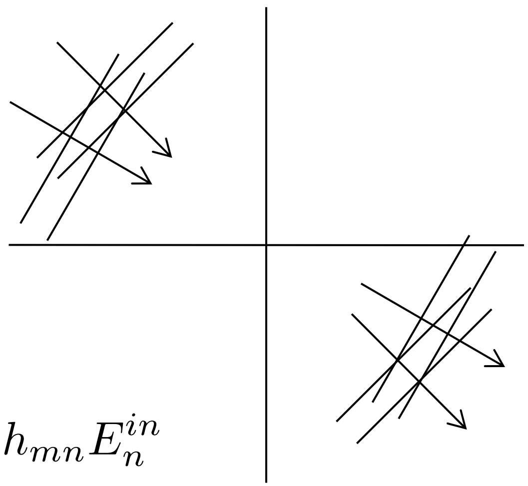
$$H = \begin{pmatrix} h_{1,1} & h_{1,2} & \dots & h_{1,N} \\ h_{2,1} & h_{2,2} & \dots & h_{2,N} \\ \vdots & & \ddots & \vdots \\ h_{M,1} & h_{M,2} & \dots & h_{M,N} \end{pmatrix}$$

=

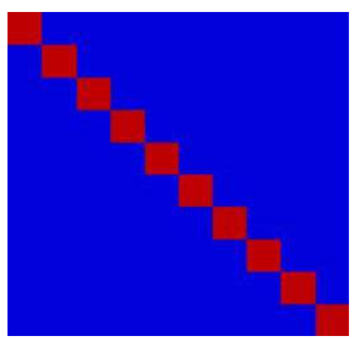


How should it look like?

Free space

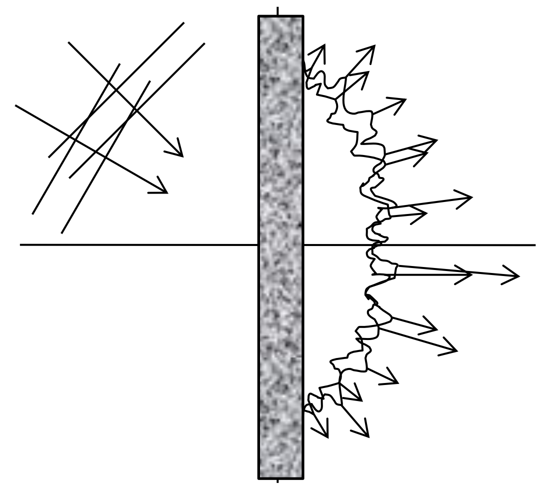


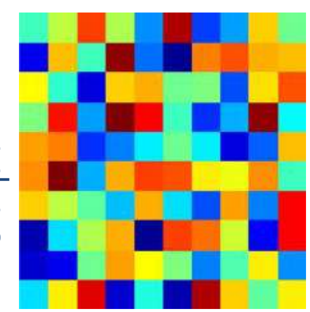
$$E_m^{out} = \sum_n^{1..N} h_{mn} E_n^{in}$$



Identity Matrix

Multiple-scattering sample

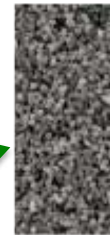




Seemingly Random Matrix

Measuring the monochromatic transmission matrix

SLM : matrix of pixels

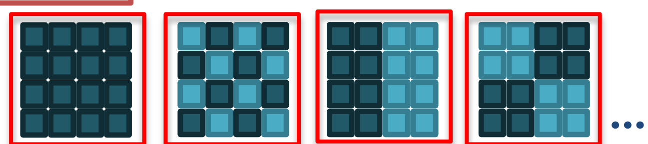


camera CCD : matrix of pixels

Thick layer of paint=
"Ideal" system

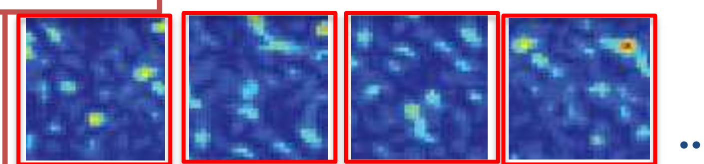
- Linear
- Multiple scattering
- Stable
- No absorption

input



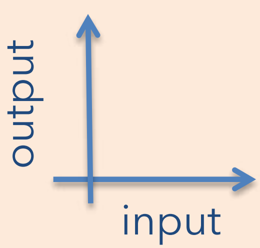
Hadamard vectors (phase-only basis)

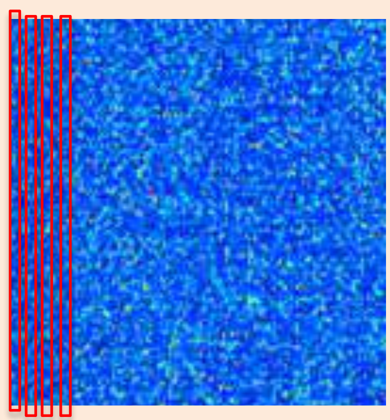
output



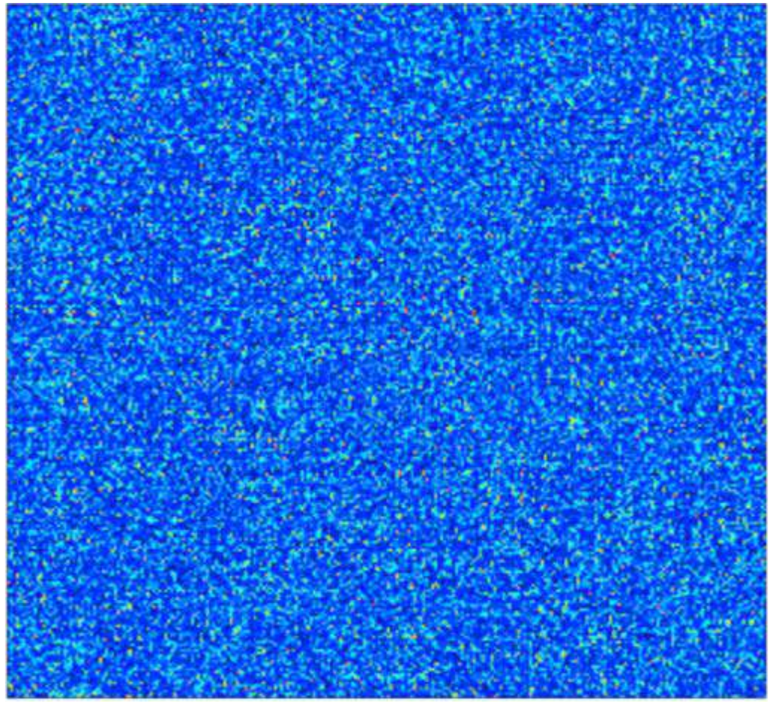
Amplitude measurement:
digital holography

Transmission matrix





And a few minutes later….



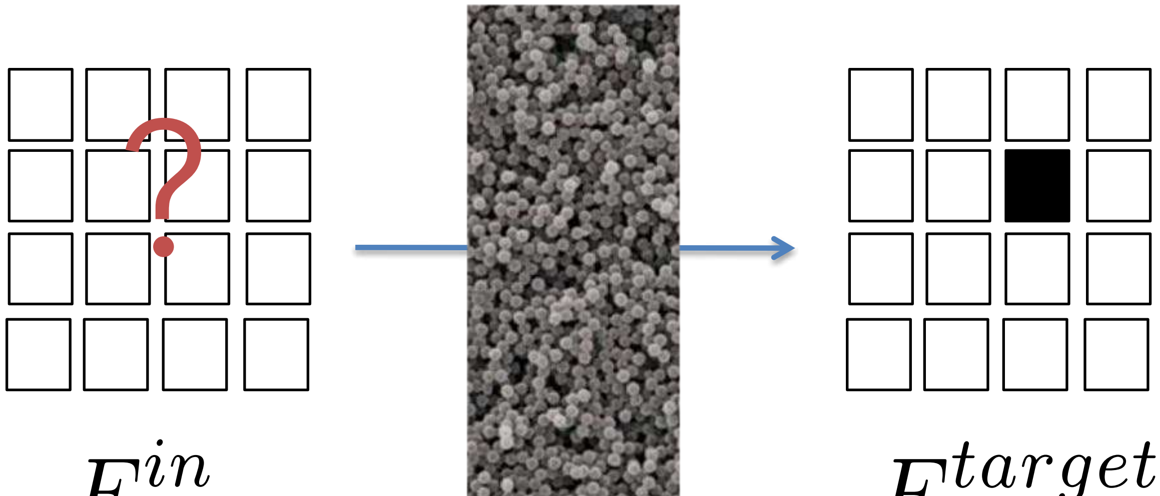
Transmission matrix

"signature" of the random medium
=
Useful as long as the medium is stable

Paint :
>1 hour ,
biological sample
<1ms !!!

Propagation = "near-perfect" mixing of information

Exploiting H : focusing



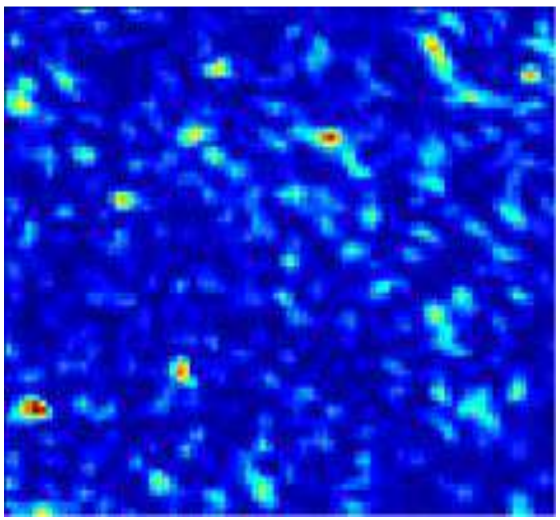
E^{in} E^{target}

Can H tell us what input will give a given output?

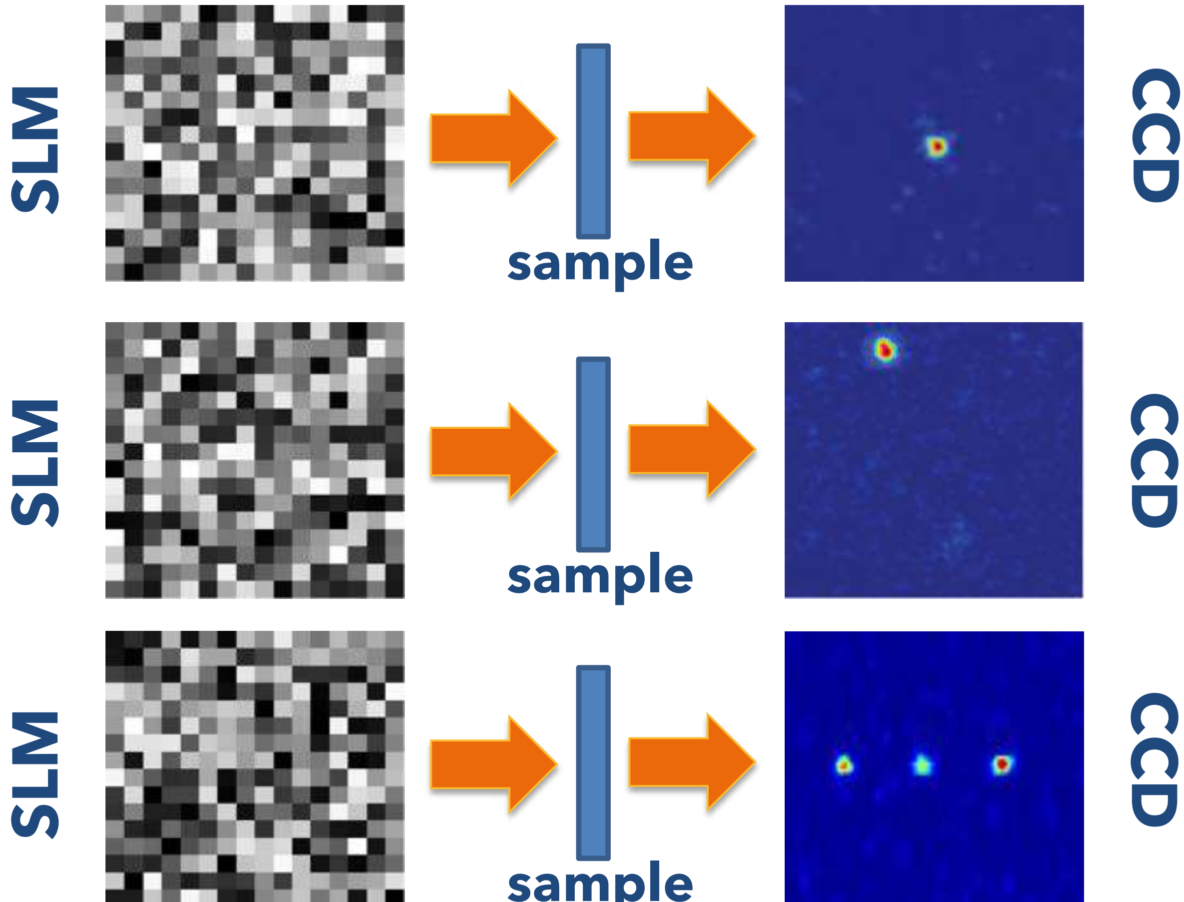
YES: $$E^{in} = H^{\dagger} E^{target}$$

Two interpretations : Phase-conjugation
Time-reversal

Exploiting H : focusing



Plane wave illumination

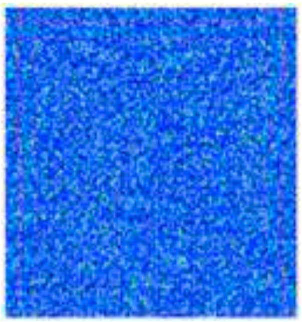


Popoff et al. Phys. Rev. Lett. 104,100601 (2010)

A tool for mesoscopic physics?

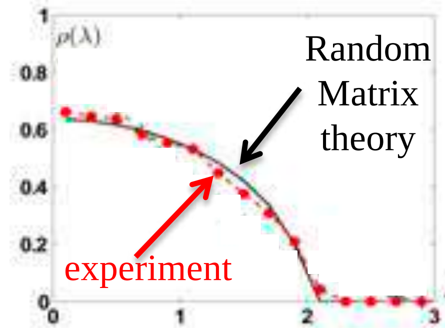
The matrix contains (some) information about the medium : SVD

singular values λ_i = transmission amplitudes
singular vectors = input output modes



Transmission matrix (exp)

The **(partial)** transmission matrix of a **multiply scattering medium** follows a very general prediction from **random matrix theory**

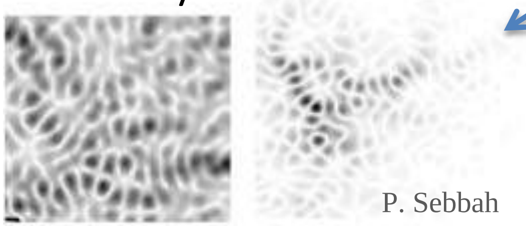


Eigenvalues distribution

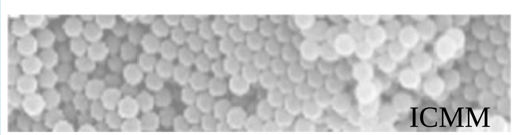
Disordered medium = perfect mixer

The hope : Complete matrix = mesoscopic effects ?

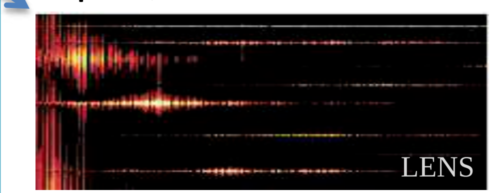
Localized/extended modes



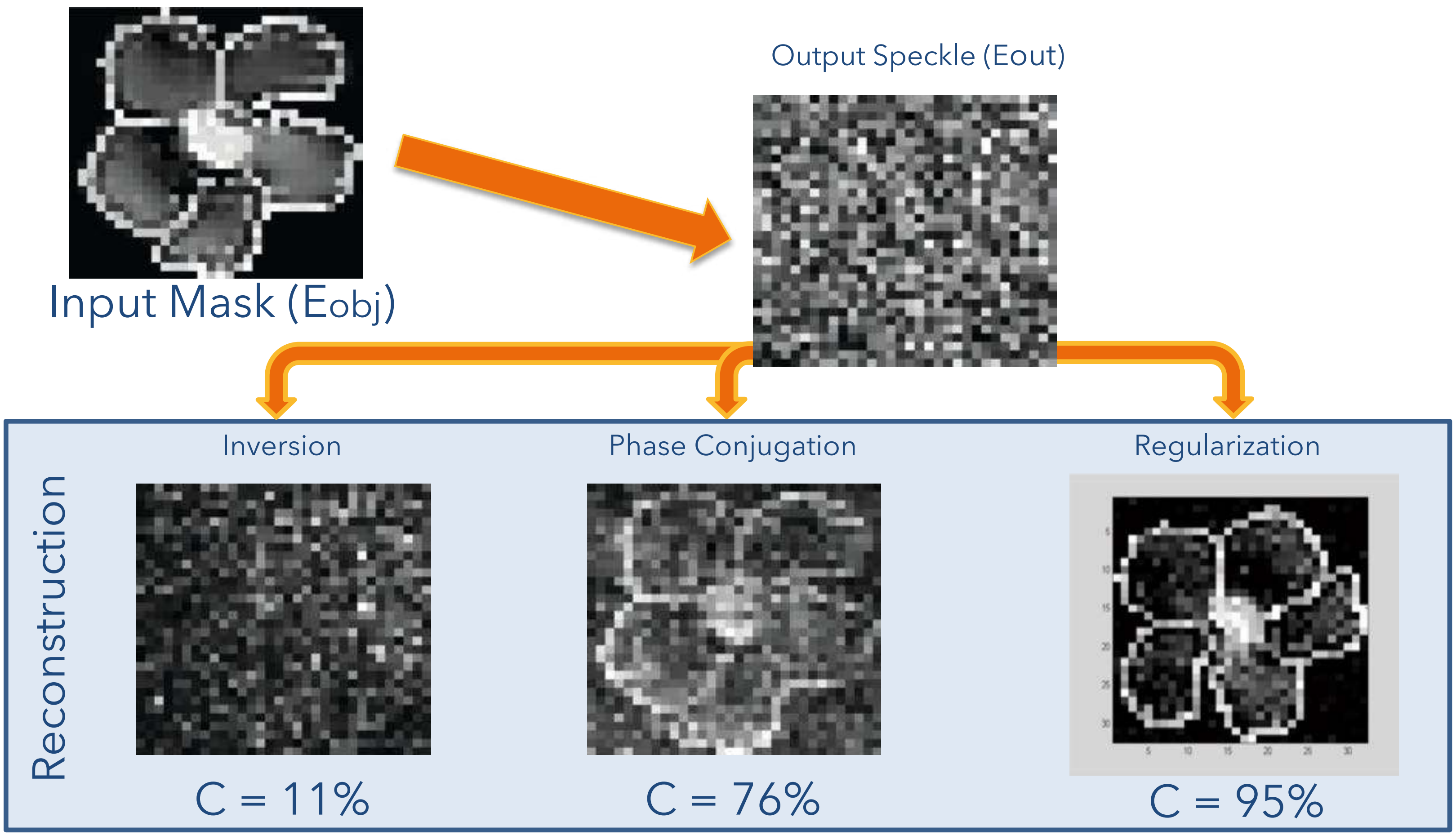
Interplay order/disorder



Open/closed channels



Experimental Results



Note : There is no assumption (prior) on the image

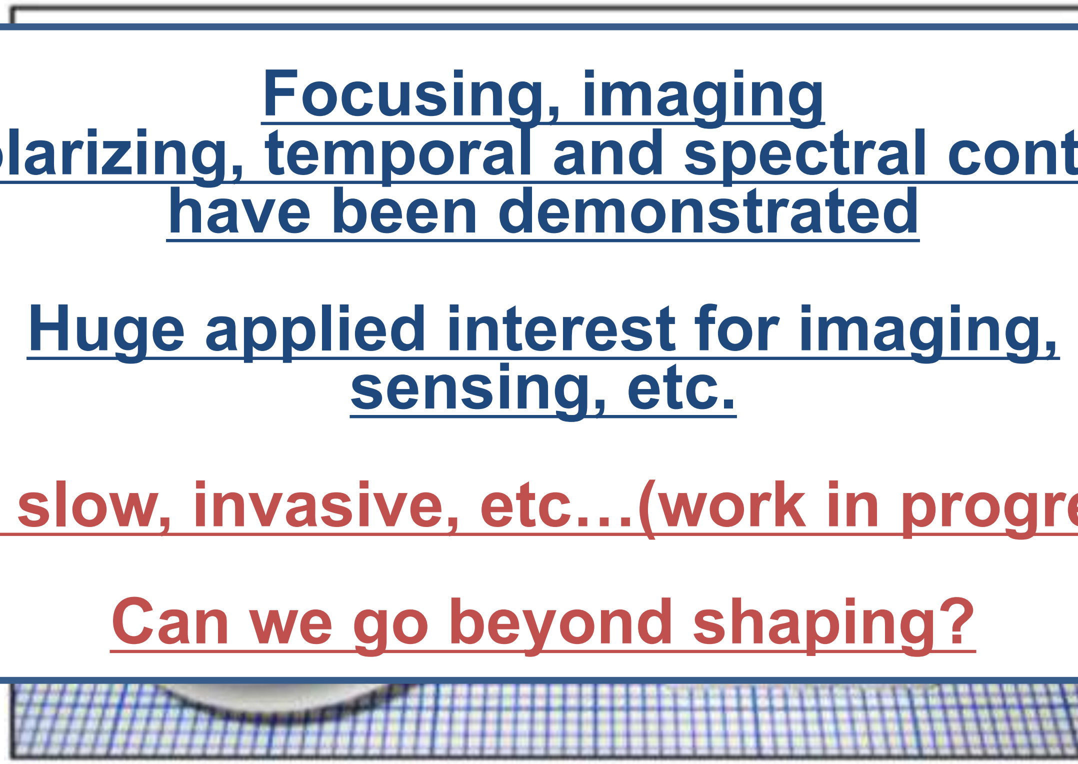
Popoff et al. Nature Communications 1,78 (2010)

Viewpoint Physics

Physics **3**, 22 (2010)

The information age in optics: Measuring the transmission matrix

Elbert G. van Putten and Allard P. Mosk



Focusing, imaging
Polarizing, temporal and spectral control have been demonstrated

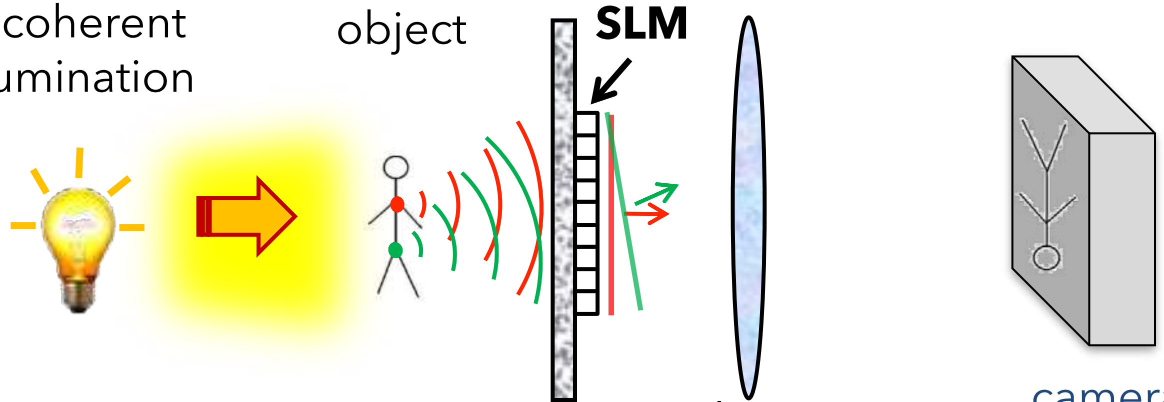
Huge applied interest for imaging, sensing, etc.

But slow, invasive, etc…(work in progress)

Can we go beyond shaping?

Thin scattering sample – « angular memory »

Incoherent illumination



thin scattering medium

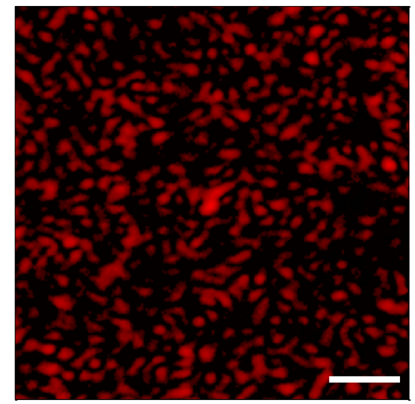
= **"scattering-lens"**

lens

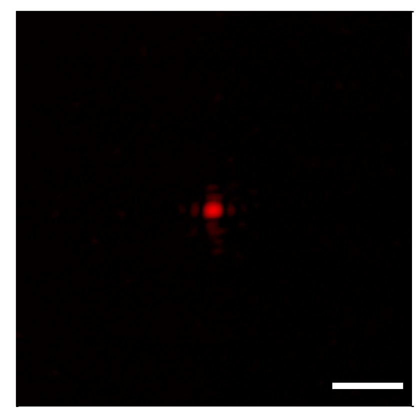
Real-time tracking

Raw CCD image:

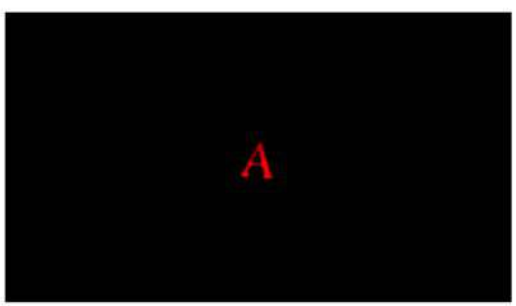
SLM off



SLM optimized



Spatially incoherent light, filtered

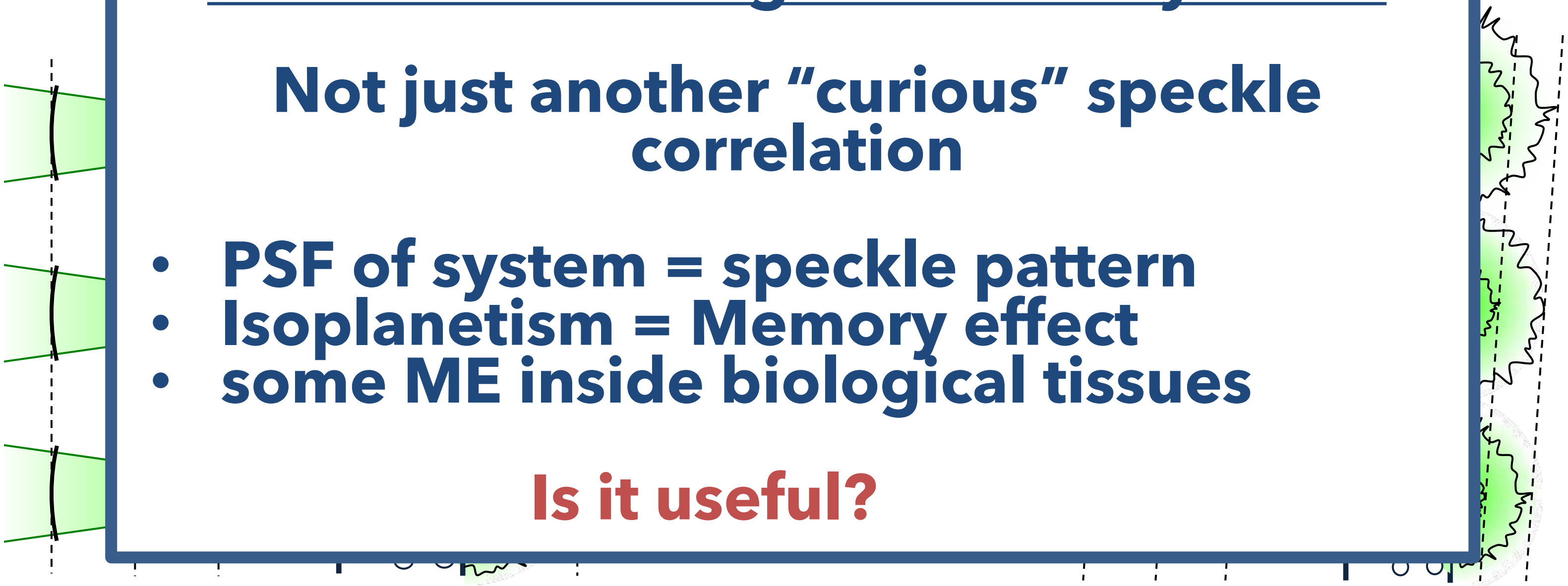


Extended object

Katz, Small, Silberberg, ***Nature Photonics***, *6, 549-553 (2012), courtesy of Ori Katz*

See also : Vellekoop, I. M., & Aegerter, C. M. (2010).. Optics Letters, 35(8), 1245–1247.

The memory effect – intuitive picture



Take home message on Memory effect

Not just another "curious" speckle correlation

- **PSF of system = speckle pattern**
- **Isoplanetism = Memory effect**
- **some ME inside biological tissues**

Is it useful?

Field of view in the diffusive regime (L>>l*)

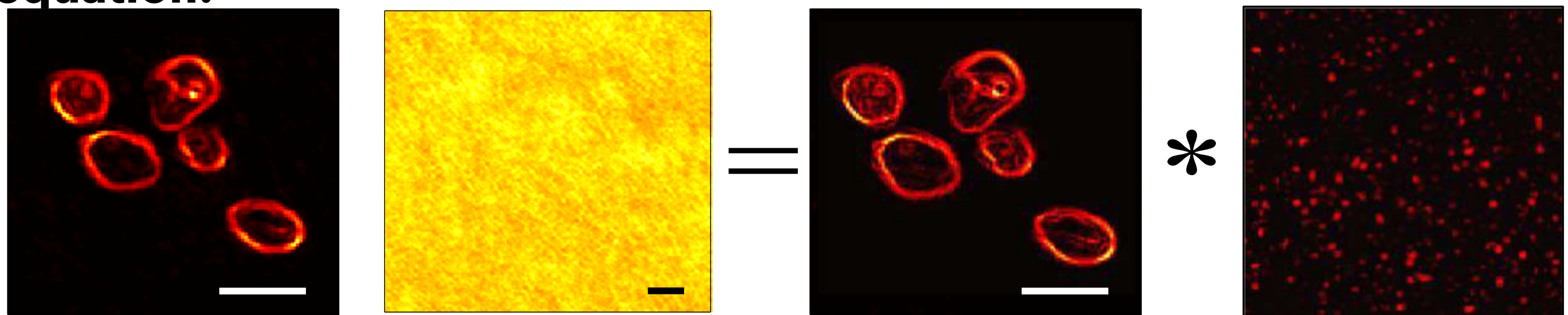
$$\theta_{max} \approx \lambda / 2\pi L$$

- **L =** medium's thickness (in transmission)
- Works <u>WHATEVER</u> the scattering properties of the medium
- Does <u>NOT</u> depend on the exact scattering properties of the medium
- Speckle translation <u>FAR AWAY</u> from the scatterer (not inside)

Retrieving an image from the speckle

The incoherent imaging equation:

$$I(x) = O(x) * PSF(x)$$

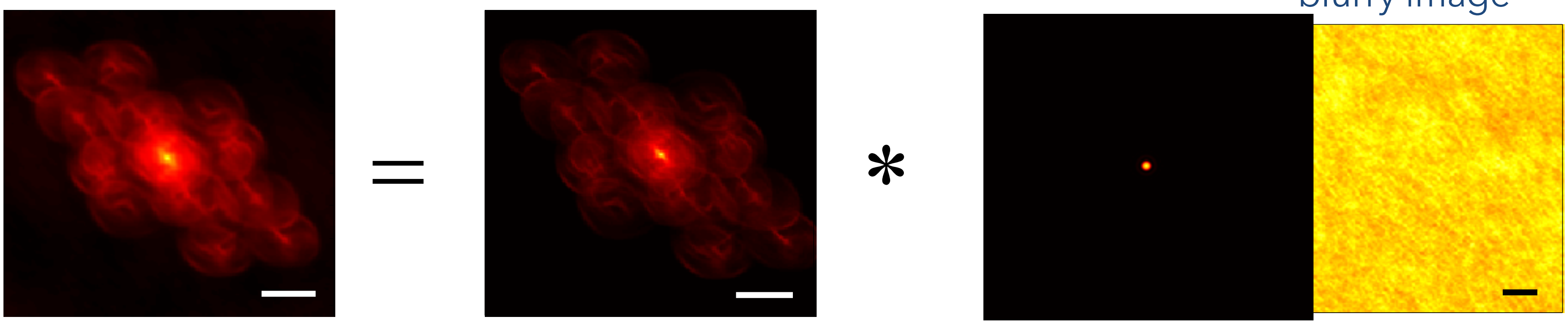


'Memory effect' [1,2]
=
Shift-invariance
for: $\delta\theta < \lambda / 2\pi L$

[1] Freund et al. PRL 61 (1988)
[2] Feng et al. PRL, 61 (1988)

$$I(x) \star I(x) = O(x) \star O(x) * PSF(x) \star PSF(x)$$

blurry image

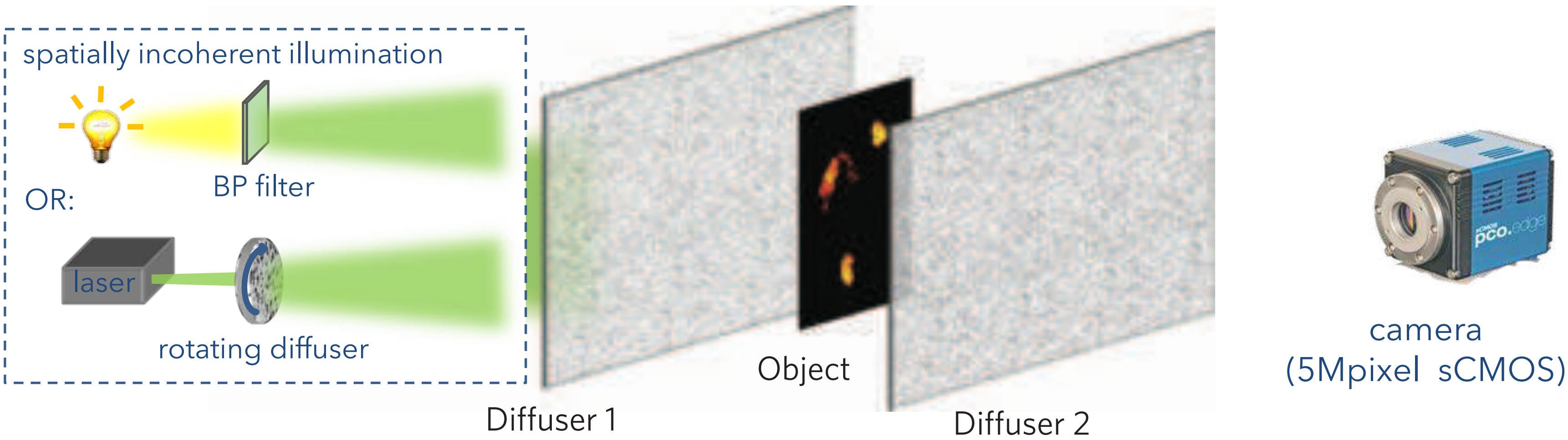


Phase-retrieval (Priors: support, real, non-negativity)

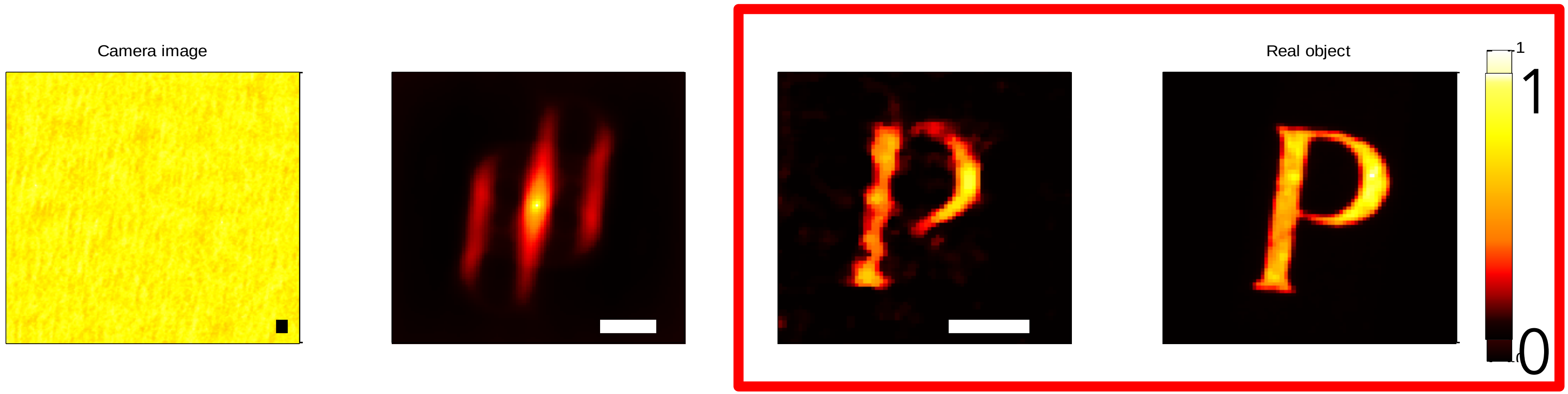
(thickness = **L**)

Katz, Heidmann, Fink, Gigan, ***Nature Photonics*** 8, 784 (2014) [see also Bertolotti et al. Nature 2012].

Real-time noninvasive imaging - experiments



Through an Optical diffuser:



Katz, Heidmann, Fink, Gigan, ***Nature Photonics*** 8, 784 (2014)

Can it work with something as simple as a camera phone ?

Katz, Heidmann, Fink, Gigan, ***Nature Photonics*** 8, 784 (2014)

Can it work with something as simple as a camera phone?

Interesting features:

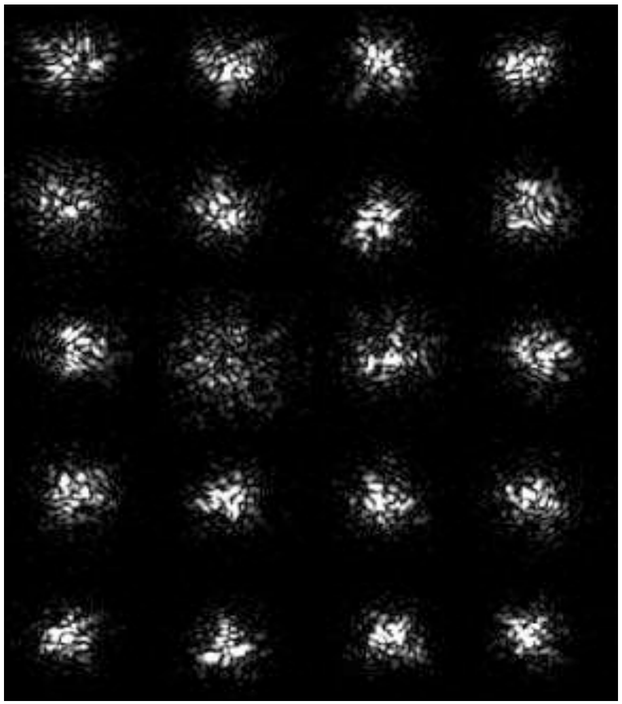
- Single-shot (real-time acquisition)
- Lensless
- Diffraction-limited resolution
- Infinite depth-of-field
- Simple: camera-phone only…

Katz, Heidmann, Fink, Gigan, ***Nature Photonics*** 8, 784 (2014)

Standing on the shoulder of the giants: ***Stellar interferometry***

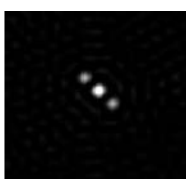
Labeyrie's technique[1] (1970)

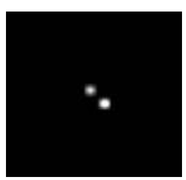
Many short-exposure images, $I_n(x)$



Christoph Keller, Leiden Uni.

$<I_n>$ $<I_n \star I_n>$ object

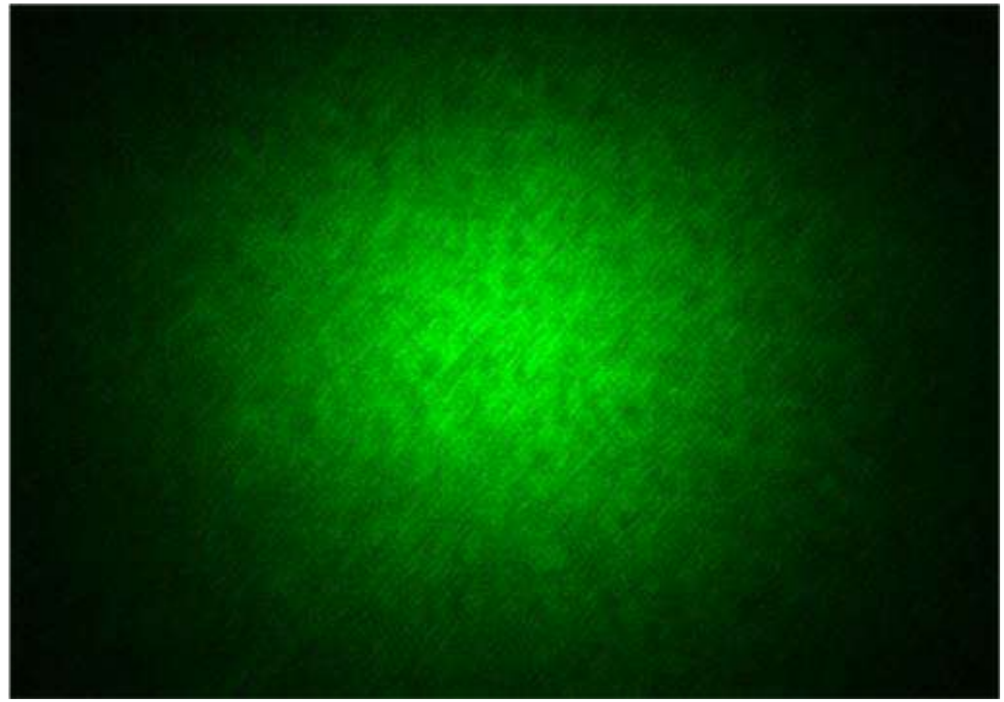




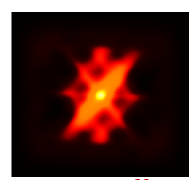
[1] Labeyrie, Astron. Astrophys. 6, 85 (1970).

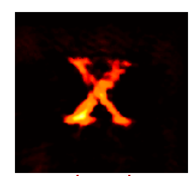
Our approach

A single 10Mpixel image (>10^6 speckles)



$I \star I$ object





Main differences: 1) Diffuse light; 2) *spatial* rather than *temporal* averaging (speckle 'ergodicity')

What is the mean path length in multiple light scattering ?

TECHNISCHE UNIVERSITÄT WIEN

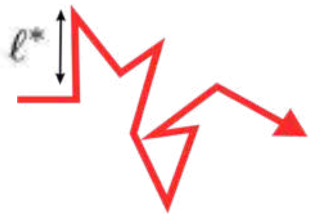
Institut Langevin
ONDES ET IMAGES

R. Savo, R. Pierrat, U. Najar, R. Carminati, S. Rotter, S. Gigan,
Observation of mean path length invariance in light-scattering media
Science Vol. 358, Issue 6364, pp. 765-768 (2017)

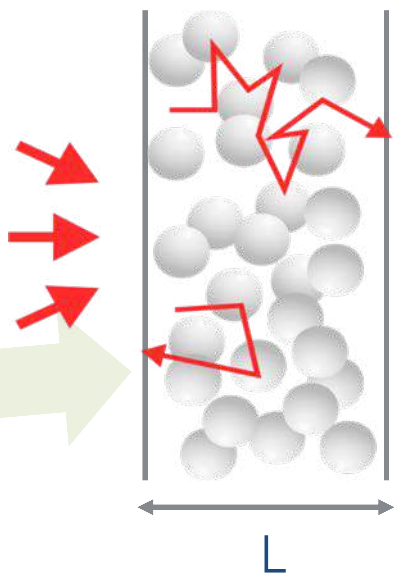

R. Savo (ONG-ETH)

Scaling of optical path lengths

<u>EVERY</u> essential features scales with the <u>transport mean free path</u>



Slab geometry



Reflection

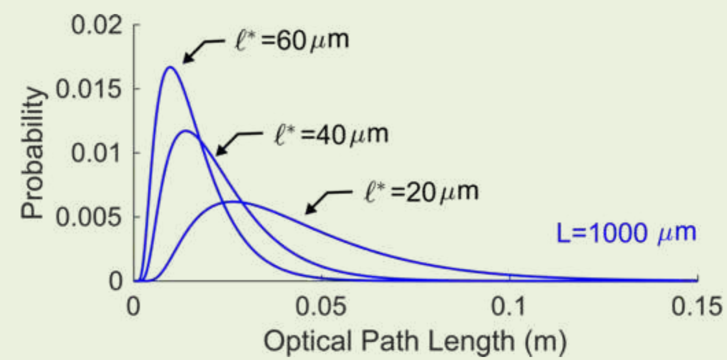
- Reflection intensity:

$$R = 1 - T$$

- Reflection time :

$$\langle \tau_r \rangle \propto l^*$$

Transmission



- Total Transmission "Ohm's law »

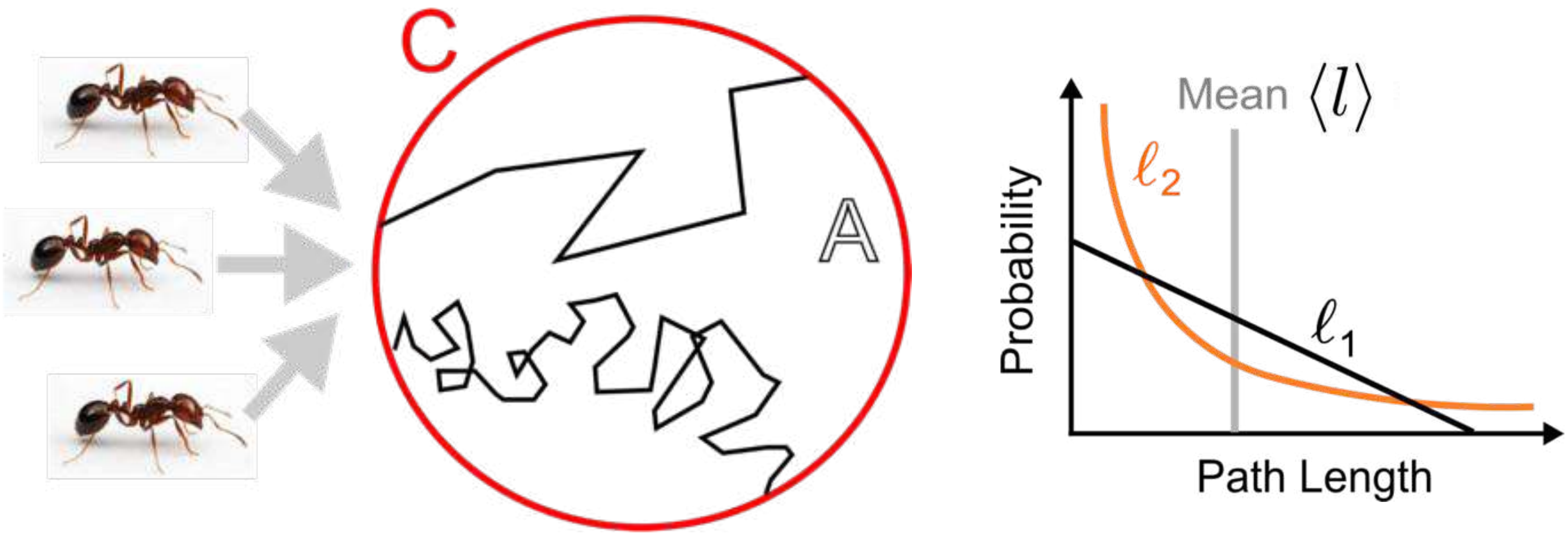
$$T \propto l^* / L$$

- Transmission (Thouless) time :

$$\langle \tau_t \rangle \propto L^2 / l^*$$

A surprising property of diffusive random walks

averaging over all possible inputs…



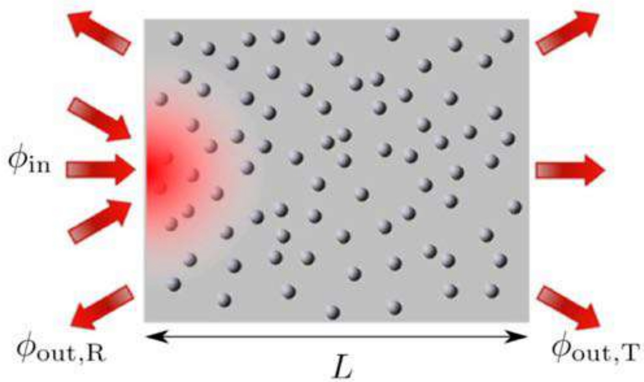
in 3D $$\langle l \rangle = 4\frac{V}{S}$$

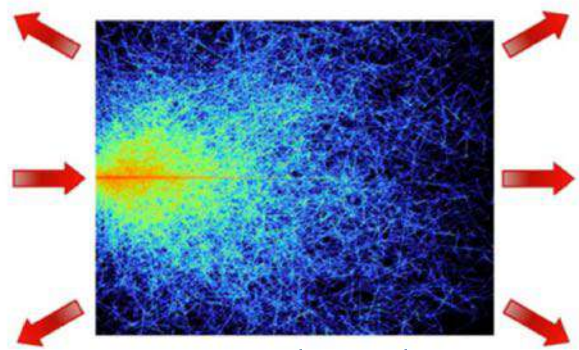
…The mean path length is invariant !
(does not depends on the random walk details, only on the geometry)

Blanco and Fournier, An invariance property of diffusive random walks, EPL 61, 168 (2003)

Theory for wave scattering

In 3D *with* and *without* resonances (in the diffusive regime):

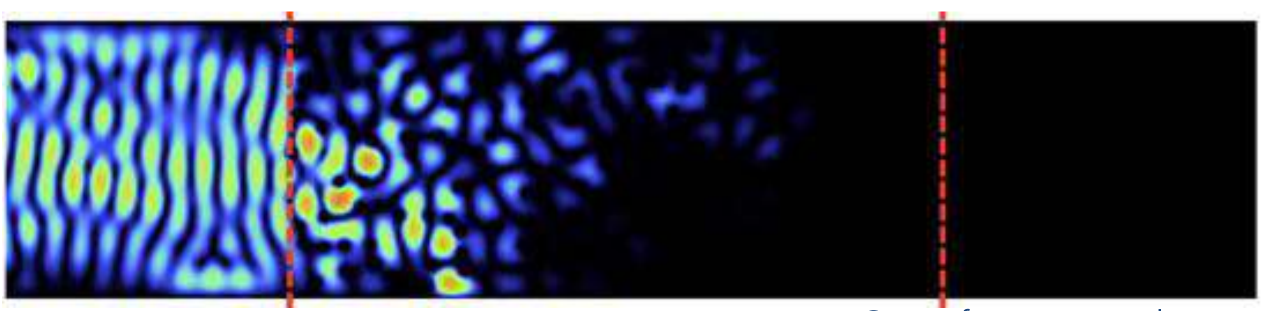




Monte Carlo simulations

$$\underbrace{\langle s\rangle}_{\text{average path}} = \overbrace{v_E}^{\text{Energy velocity}} \underbrace{\langle t\rangle}_{\text{average time}} = \frac{4V}{\Sigma}$$

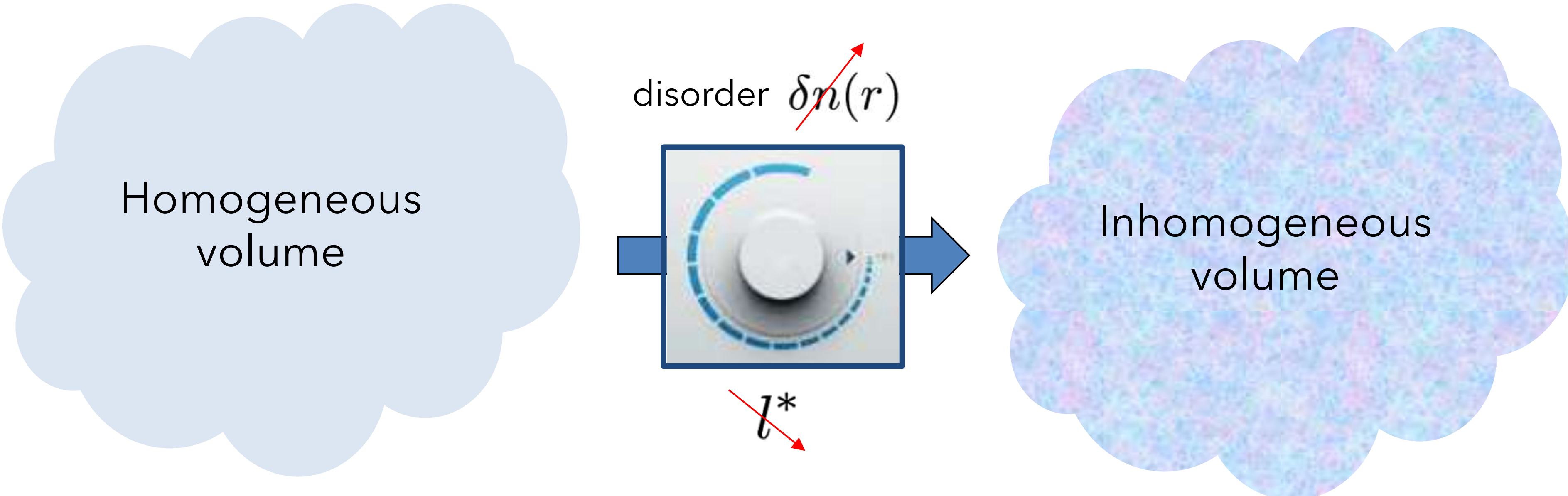
In 2D waveguide in the Anderson localization regime



Green function simulations

R. Pierrat et al., An invariance property of wave scattering through disordered media, PNAS (2014)

1-slide underlying physics



- The mean path-length only depends on the Density of State (DOS)
- DOS only depends on overall geometry (Weyl Law)

Important consequence: valid not just for disorder but for **any** distribution of refractive index (ordered, correlated…)

R. Pierrat et al., An invariance property of wave scattering through disordered media, PNAS (2014)

Any observations of such invariance?

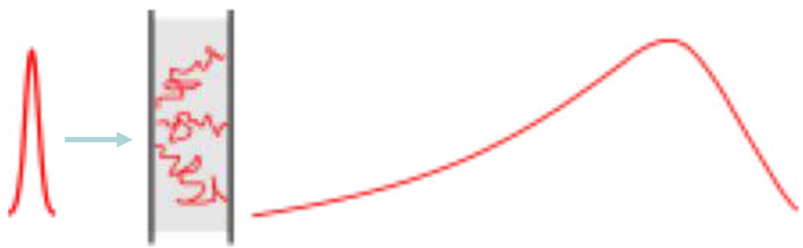
Does light have the same optical path length here?

No observation so far

but nobody actually tried!

…so we tried!

Time-of-flight measurement?

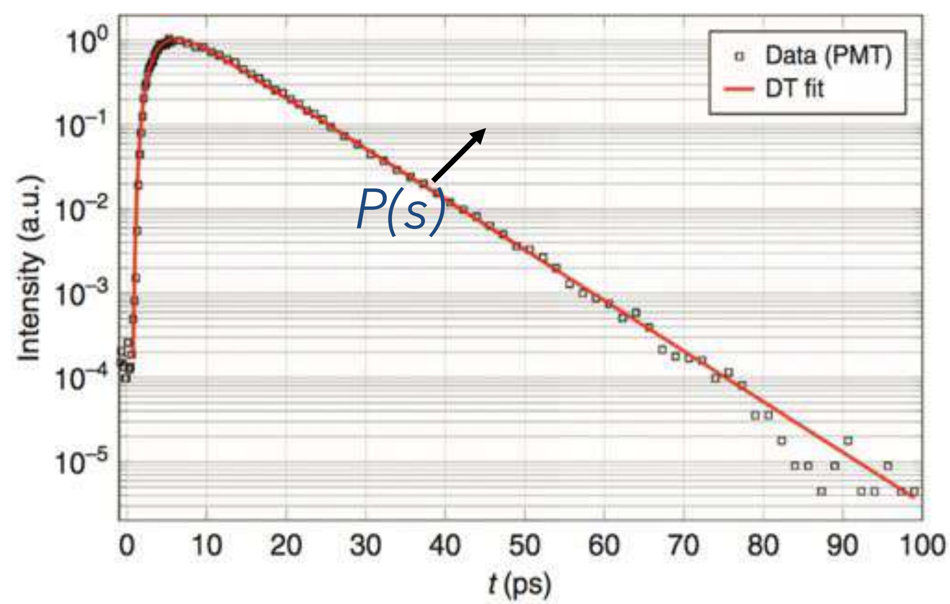


~~Time-of-flight measurements:~~

~~Access to the complete distribution of path length $P(s)$~~

Requires:

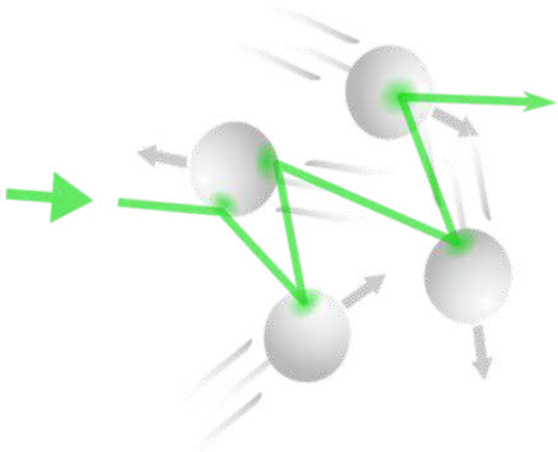
- Femtoseconds resolution
- Non-linear or interferometer detection
- High dynamic range in time and intensity
- Complex detection scheme
- Typically solid samples



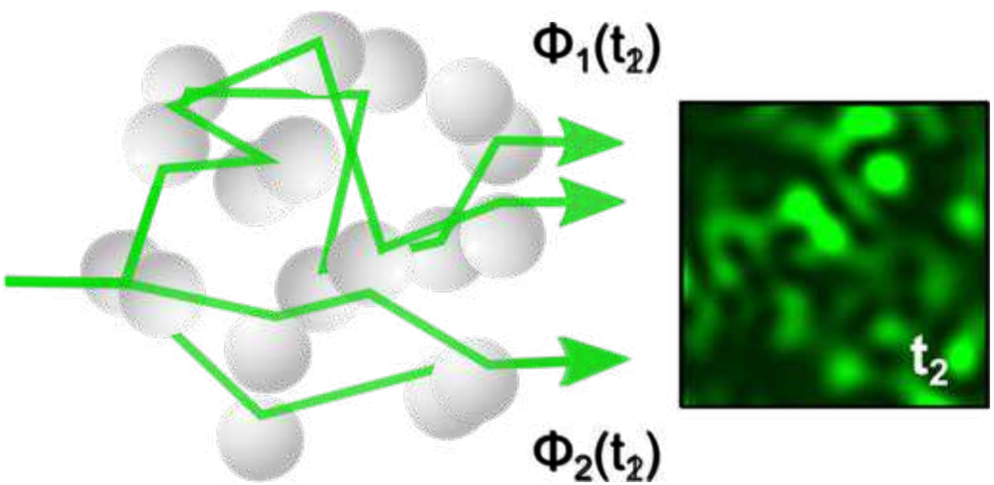
L. Pattelli, R. Savo et al., Light: Science & Application (2016)

Accessing the path length distribution with a CW laser

Dynamic media



Speckle evolve in time due to brownian motion



Temporal field autocorrelation:

$$g_E(\tau) = |\langle E^*(\tau)E(0)\rangle|^2 / |\langle EE^*\rangle|^2$$

Diffusing Wave Spectroscopy (DWS)

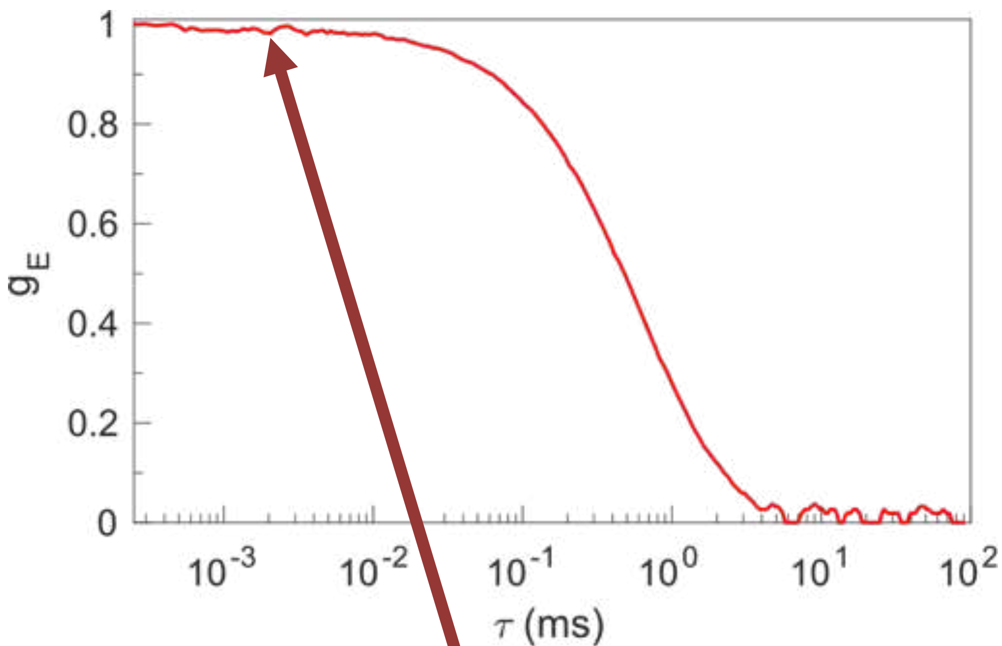
$$g_E(\tau) = \int_0^\infty ds P(s) \exp\left(-\frac{s}{\ell^*}\frac{2\tau}{\tau_0}\right)$$

G. Maret and P. E. Wolf, Multiple light scattering from disordered media. The effect of brownian motion of scatterers. *Zeitschrift für Physik B Condensed Matter* (1987).

D.J. Pine, D.A. Weitz, P Chaikin, and E. Herbolzheimer, Diffusing-Wave Spectroscopy. *Physical Review Letters* (1988).

Extracting the mean path length

Diffusing Wave Spectroscopy (DWS)

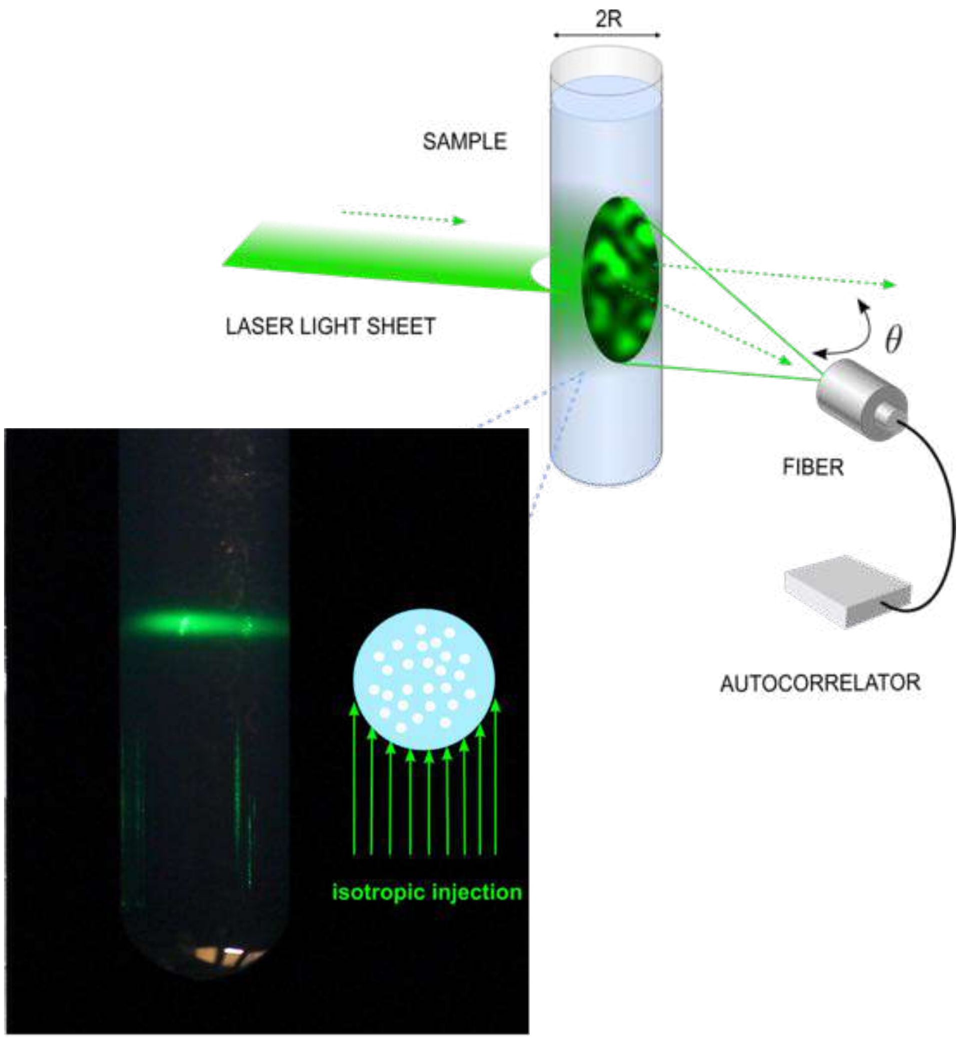


$$g_E(\tau) = \int_0^\infty ds P(s) \exp\left(-\frac{s}{\ell^*}\frac{2\tau}{\tau_0}\right)$$

$$\langle s \rangle = -\left.\frac{dg_E}{d\tau}\right|_{\tau=0} \frac{\ell^* \lambda_0^2}{8\pi^2 n^2 D}$$

Slope at the origin
=
Direct measurement of
<s>

Experiment



Samples:

- Polystyrene beads in water
- Controlled concentration & size
- No absorption

Cylindrical geometry:

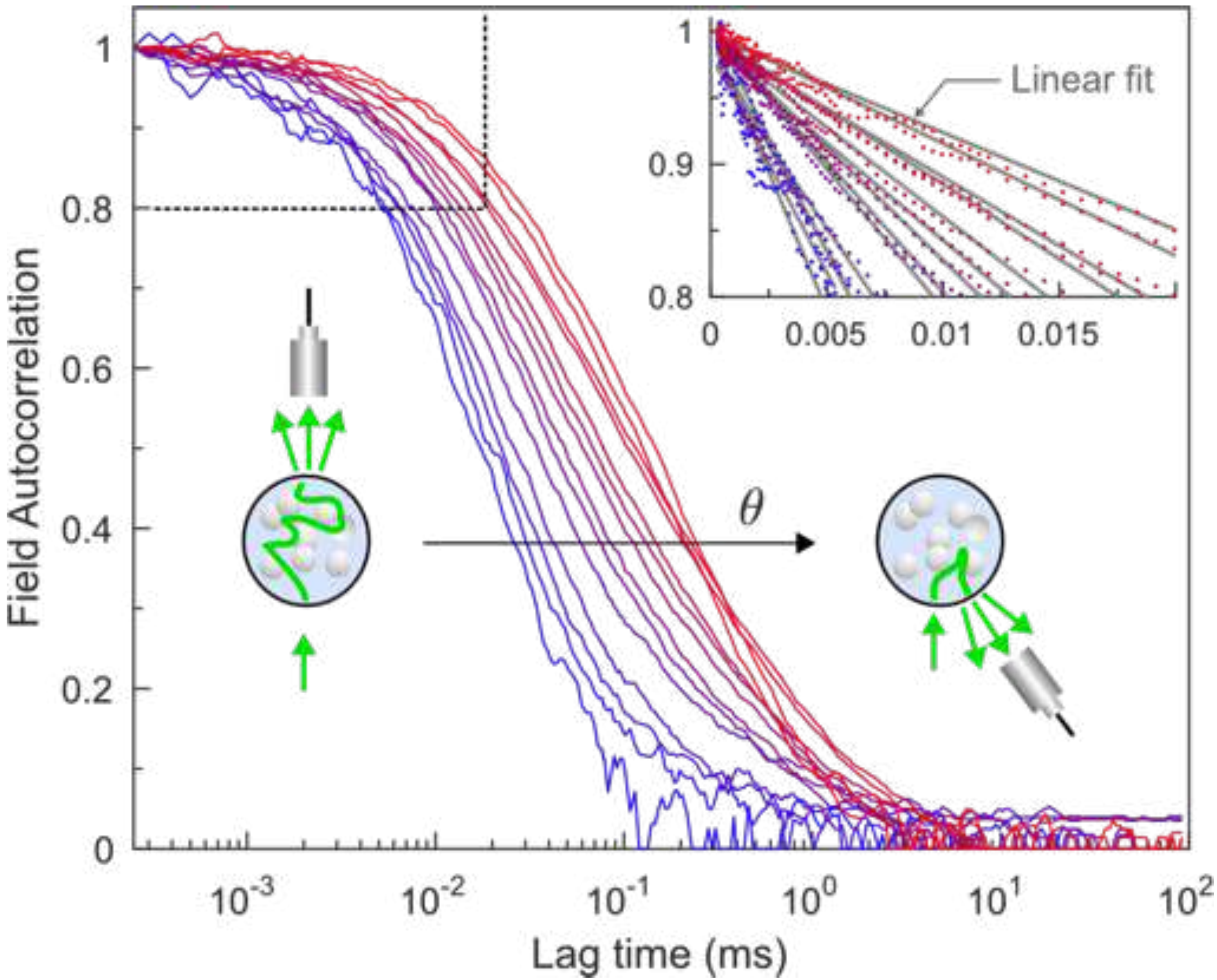
- Expected mean path length
  $<s>=2R=8.45$mm
- + Modification due to outer glass
- Light sheet ⟶ Isotropic illumination

Detection:

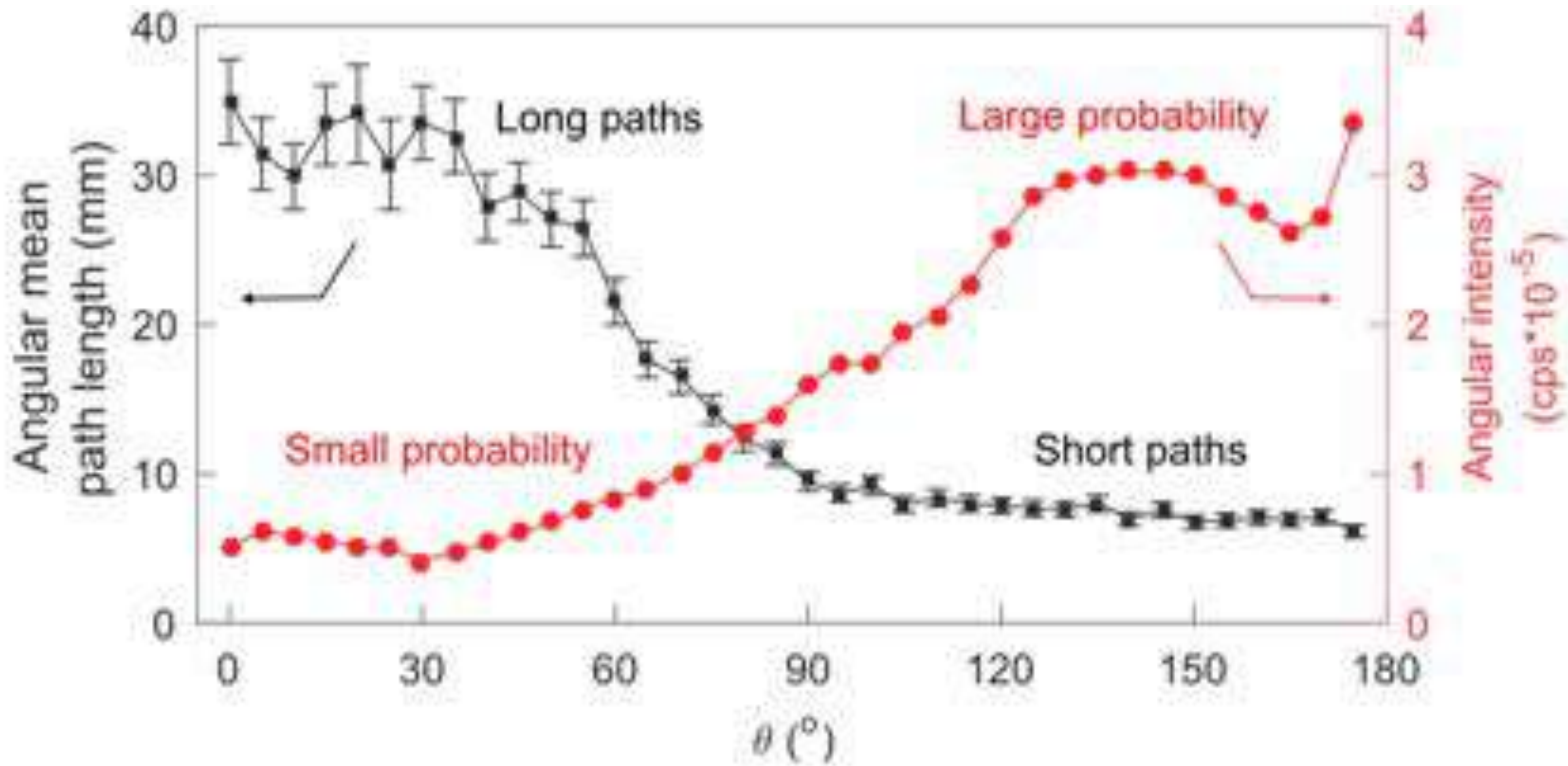
- 0 =< angle <=175 degrees

Intensity measurement
(Photon counting regime)

Measurement of the mean path length



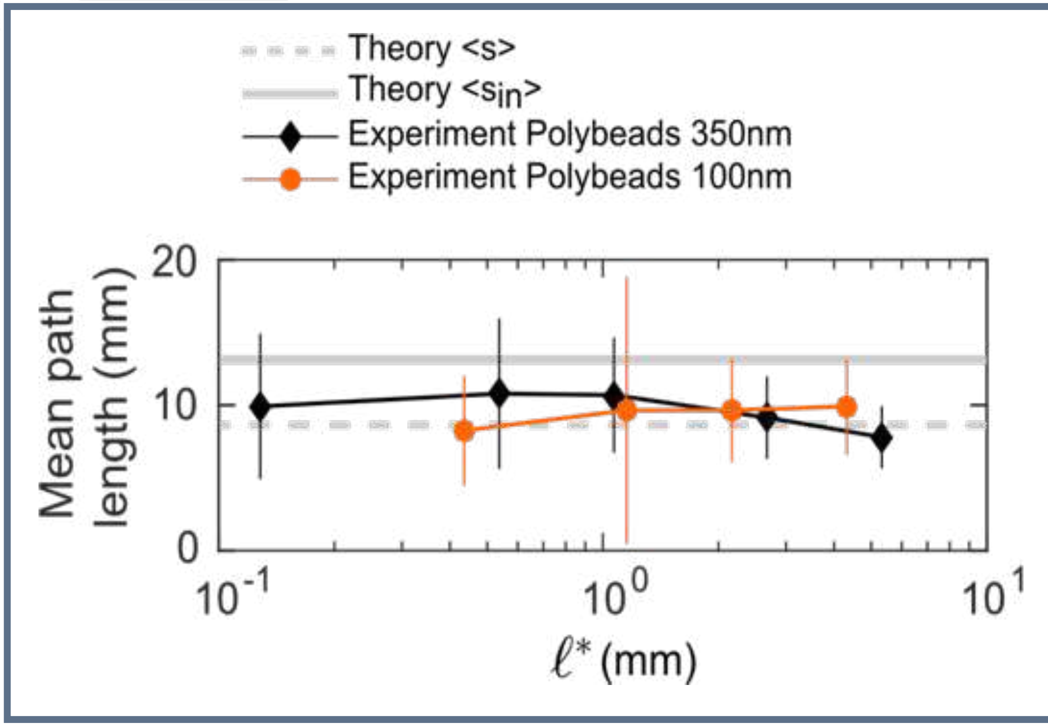
Angular measurement and averaging

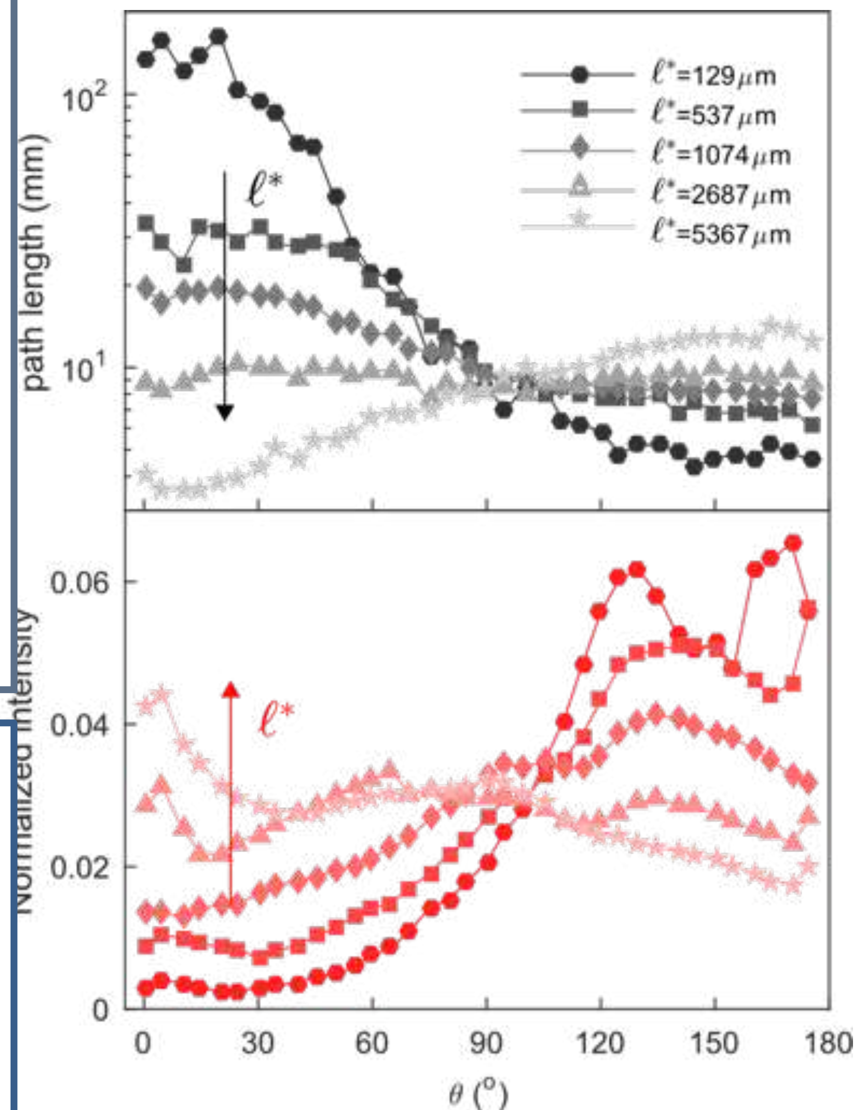


Global mean calculated as

$$\langle s \rangle = \frac{\sum_i \langle s \rangle(\theta_i) I(\theta_i)}{\sum_i I(\theta_i)}$$

Observation of the invariance?





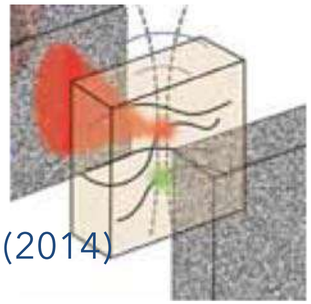
- ✓ Verification of the invariance of the mean path length on the disorder strength
- ✓ Independent of the disorder strength
- ✓ Valid whatever the microstructure
- ✓ valid for all types of waves
- ✓ application in light trapping? Photonic crystal design ? Sensors?

R.Savo et al.,
Science 358(6364) 765 (2017)

Other « complex optics» Projects in the group

Deep Imaging in Scattering Media

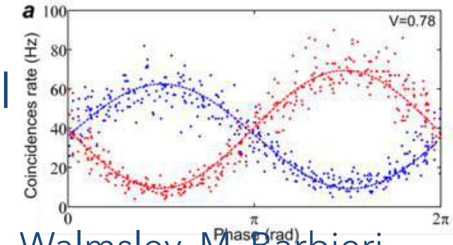
Wavefront Shaping
+
Photoacoustics
(collab. E. Bossy)



T. Chaigne et al, NPhot. 8, 58–64 (2014)

Complex quantum Optics

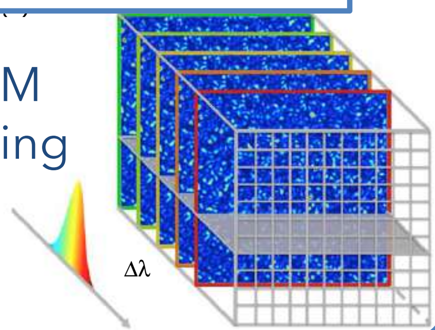
Non Classical state
Propagation/control
In complex media



Collab B. Chatel, B. Smith, Walmsley, M. Barbieri
Optics Letters (2014) Sci. Adv. (2017)

Spatiotemporal Control

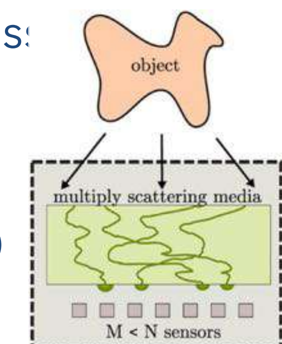
Spatial and spectral TM
Spatiotemporal focusing



Sci. Rep. 5,10347 (2015)
PRL (2016)

Compressive imaging

Exploiting natural randomness
For more efficient imaging
systems



Collab L. Daudet (IL) F. Krzakala (LPS)
A. Liutkus et al. Scientific
B. Reports 4, 5552 (2014)

Optical Computing

Exploiting randomness
For machine learning?

Startup LightOn

+ Random Laser Control by pump shaping
"the random laser tamed", Nat. Phys (2014)
Collab P. Sebbah (IL)
+ Control of disordered plasmonic
structures (collab. Samuel Grésillon, IL)

Thank you for your attention !

N'hesitez pas à demander les transparents!

Mail : sylvain.gigan@lkb.ens.fr

Webpage: www.lkb.ens.fr/gigan

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Stefan Rotter and Sylvain Gigan

Rev. Mod. Phys. **89**, 015005 – Published 2 March 2017

Stefan Rotter (TU Wien)